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WIDE-ANGLE, MULTIVIEWER INFINITY DISPLAY DESIGN

By

Robert M. Rhinehart
McDonnell Douglas Electronics Company
2600 N. 3rd Street
St. Charles, Missouri 63301

ADVANCED SYSTEMS DIVISION
Wright-Patterson Air Force Base, Ohio 45433

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This technical report has been reviewed and is approved for publication.

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Advanced Systems Division

DAN D. FULGHAM, Colonel, USAF
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A research design study was undertaken to define an extended field of view (60° x 180°) infinity image display, suitable for multiviewer use on wide-bodied aircraft simulators. Mosaicking of single channel units, both reflective and refractive was investigated, along with extended field, off-axis reflective systems. Major emphasis was placed on the investigation of extended field of view, off-axis reflective systems. Various figured screen and mirror combinations, ranging from spherical to high order aspherics, were designed and evaluated. Two specific designs were selected, optimized and evaluated over an extended viewing volume.

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WIDE-ANGLE, MULTIVIEWER INFINITY DISPLAY DESIGN

1. SUMMARY

1.1 Study Objectives

The objectives of this study were to survey the state of the art in infinity image displays, and to investigate the possibility of arriving at a wide-angle system (180°H x 60°V), to be used in the multiviewer configuration, typical of large cabin aircraft simulators. The intent was to provide a large viewing volume (3- by 5- by 1.5 ft) sufficient to permit the pilot, copilot, and instructor or observers to view the same scene simultaneously. The system approach offering the greatest potential for achieving these goals was to be selected, designed and evaluated.

1.2 Study Approach

The study approach was to first evaluate the existing infinity display units, both reflective and refractive. These units, when mosaicked together to obtain the required field of view, were evaluated over an extended viewing volume. The third system approach evaluated was an off-axis, reflective design consisting of a single mirror large enough to cover the total required field of view.

1.2.1 Reflective On-Axis Design. The first wide-angle system approach considered was the mosaicking of single-channel CRT-Beamsplitter-mirror units in a configuration similar to the system on the F-4E no. 18 simulator at Luke Air Force Base (see Figure 10). The principal difficulty with this type of system is that image registration and continuity is difficult to maintain over an extended viewing volume. A two-window scale model was used to demonstrate and evaluate these characteristics. Photographs were taken of the images at selected off-axis positions such that the images obtained corresponded to those which would be seen from a twelve-channel mosaicked system. The photographs were then spliced together to show the total scene as observed from various positions in the viewing volume. This very readily demonstrated the image breakup and geometric distortion due to off-axis viewing. Therefore this system approach will not meet the specified requirements where an extended viewing volume is required.

1.2.2 Refractive On-Axis Design. The other possible single-channel system which could be mosaicked to obtain extended field of view is in the in-line refractive system using large diameter lenses. The characteristics and limitations of refractive systems in general, including their differences from and similarities to reflective systems, are generally known. Therefore, a specific refractive system was not designed, but, instead, the problems associated with mosaicking and off-axis viewing were discussed and compared with the mosaicked reflective system. A computer raytrace analysis (from the pilot's eye position) was made on one channel of a wide-angle refractive system that the Air Force Human

Resources Laboratories has at Wright Patterson Air Force Base. (See Figure 16.) Collimation and geometric distortion data show that this system does not meet the respective specification requirements for this contract. (See Appendix A for requirements.)

Modular-type mosaicked systems, whether reflective or refractive all exhibit three basic limitations when viewed from more than a few inches off-axis. These are (a) image or field separation (between adjoining sections), (b) geometric distortion (mapping), and (c) collimation errors (apparent image distance). The short radius of curvature mirrors used in modular reflective systems, and the relatively short focal length lenses used in refractive systems, essentially restrict the acceptable viewing volume to single pilot applications. However, these major limiting characteristics can be reduced to acceptable levels or eliminated by going to an off-axis, single large mirror system. The image or field separation is eliminated by the continuous mirror, and screen imagery. The geometric distortion and collimation errors can be reduced by using a long radius of curvature mirror, with screen shape and location optimized for the prime viewing area.

1.2.3 Off-Axis Reflective Design. The last system studied and the one selected as the most promising to meet the system requirements is an off-axis reflective system, consisting of a large wrap-around mirror and screen (see Figure 39). After considerable design and optimization efforts using various shaped mirrors and screens, two configurations were selected and optimized for this particular application, namely a spherical mirror and toric screen (SMTS) and a spherical mirror with a spherical screen (SMSS). These arrangements were analyzed and evaluated at selected points throughout the viewing volume. The design analysis shows that the SMSS design offers the best overall system performance throughout the required extended viewing volume.

1.3 Conclusions

The recommended design is a 132 inch radius of curvature spherical mirror with a spherical screen. The desired characteristics, as given in the statement of work, have not been met throughout the entire viewing volume in this design, but it does demonstrate the superiority of an off-axis approach. This study does show that a wide-angle infinity display is feasible for multiviewer applications.

2. INTRODUCTION WIDE-ANGLE, MULTIVIEWER INFINITY DISPLAY DESIGN

This study effort was to define and develop a design for a wide-angle, multiviewer infinity display for use in visual simulation. The display is intended to provide wide-angle color visual scenes to the cockpit crew of a flight simulator representative of the visual scenes encountered in actual flight. It is specifically intended for wide-bodied aircraft simulators which include bomber, cargo, and tanker type aircraft. It is the intent to present the same uninterrupted scene to all the crew members.

3. TECHNOLOGY REVIEW

3.1 Documentation Review

A literature search was performed first to collect and review previous work performed in this field. A number of reports pertaining to wide-angle virtual image systems including patent applications, were obtained and reviewed. Copies of the more significant reports were forwarded as additions to the monthly reports. No new technique or breakthrough was found from this search; however, the search was significant because it verified the position that there is presently no virtual image infinity system available that will meet all of the requirements for a multiviewer configuration.

3.2 System Equipment Review

A trip to Luke and Williams Air Force Bases was made during this period for the purpose of viewing the wide-angle optical systems in use on the F-4E no. 18 simulator, the Simulator for Air-to-Air Combat (SAAC), and the Advanced Simulator for Pilot Training (ASPT) installations.

The F-4E no. 18 six-channel mosaicked cathode-ray tube (CRT)-beamsplitter system (108^{o} x 48^{o}) Field of View (FOV) was examined with color synthetic terrain imagery. The optical performance of this system was quite impressive, with considerable head-motion possible for a single viewer. Image seams were not obtrusive; alignment and scene brightness were judged to be very adequate. It appears that a certain amount of cutting, splicing and hand-fitting was used to complete the vertical and horizontal alignment.

The SAAC display with synthetic terrain and a TV-inserted target aircraft was demonstrated. The very large horizontal and vertical fields were extremely impressive. Aircraft maneuvers induced very strong motion cues, although the motion system was not in operation. Image seams were again not intrusive. The ASPP system was also demonstrated, and the system optical performance was very similar to the SAAC system. It was noted that the ASPT imagery, although low resolution, appeared to be very acceptable perhaps because of its being distributed over such a wide viewing field. During a straight-in final approach to a standard runway, however, scene element breakup and blinking did disturb the total effect quite considerably.

It can be concluded that mosaicked systems are quite adequate for presenting large fields of view for single pilot aircraft simulators. In this case the viewing volume can be limited to an 8- to 12- inch sphere, where image breakup can be minimized by overlapping fields.

3.3 Aircraft Window Configurations

Information on cockpit geometry was gathered and tabulated for several wide-bodied aircraft (see Table 1). This table shows the separation of the pilot, copilot, and the observer's station where information was available. In the C-141 and C-5 cockpits, the observer's station is located midway between the pilot and copilot and displaced approximately 40 inches to the rear of the flight deck.

TABLE 1. CABIN DATA: WIDE-BODIED CRAFTS

WIDE-BODIED CRAFT	PILOT-COPILOT SEPARATION	OBS.STA.-PILOT DISTANCE	FRONT PILOT-MIRROR INDICATES MIN.RC	SIDE PILOT-MIRROR IF > FRONT	PILOT F.O.V. PLOTTED
SH-2F	34.5"		60"		
DC-9	38"		58"		
DC-8	38"		58"		
737	40"		57"		*
S-3A	40"		54"		
DC-10	42"		57"		YES
L-1011	42"		56"		YES
C-135	42"		56"		YES
747	42"		58"		YES
BAC-111	42"		54"		
727	42"		57"		*
707	42"		56"		*
C-141	46"	40"	50"	56"	YES
C-5	52"	40"	50"	56"	YES
B-52					YES
C-130B					YES

*SAME AS C-135 WINDOW CONFIGURATION

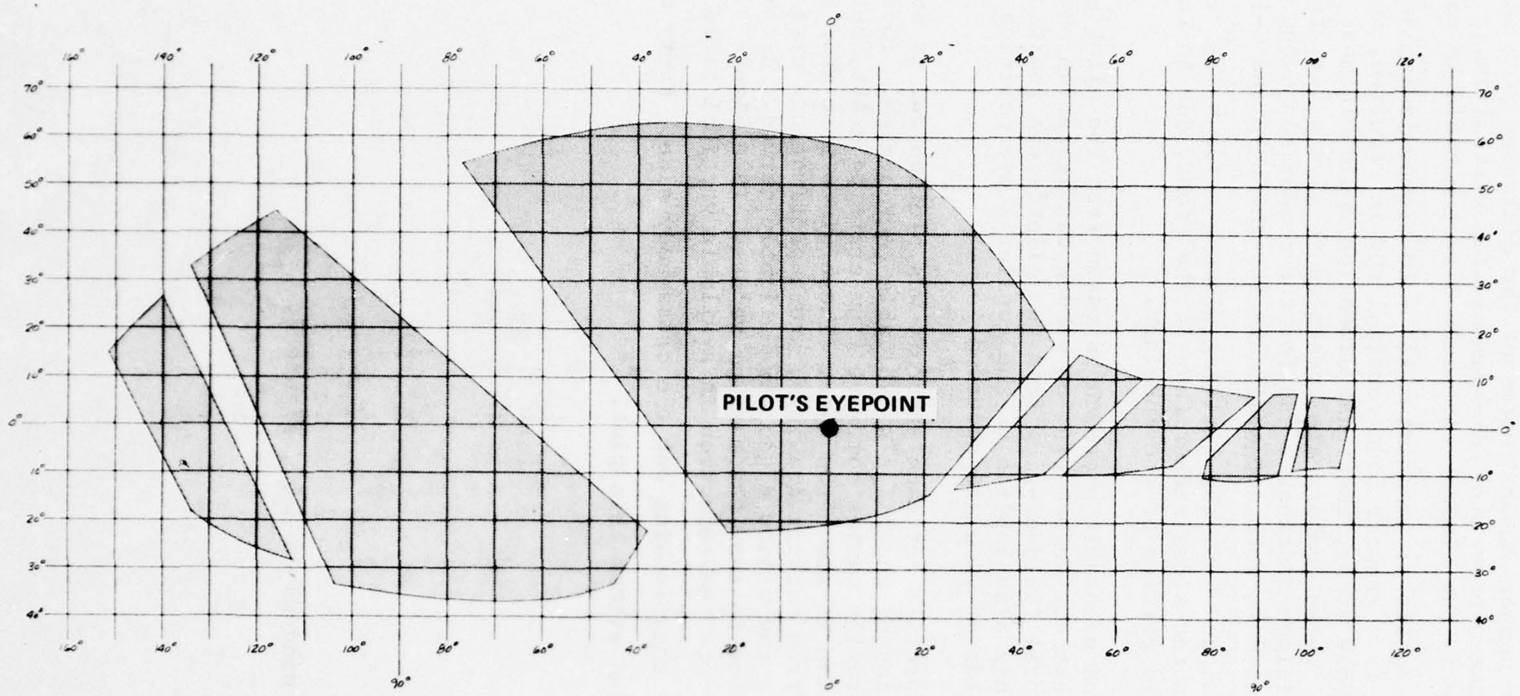
The pilot-to-mirror numbers shown represent the distances from the pilot's eyepoint to the mirror in a CRT-beamsplitter virtual image package. This distance is the closest that such a system could be mounted to the pilot's eye position, assuming a 15^{o} - 18^{o} down-viewing angle in the vertical FOV. If a greater down vertical FOV is required, and would be in the case of this study, then that dimension would, in most cases, increase somewhat. These numbers are presented to give a feel for the magnitude of the minimum distances, and for the comparison among different aircraft. These data were not available for the B-52 and C-130B.

In case of the C-141 and C-5, the limiting distances for a 180^{o} FOV display would occur on the sides rather than in the front, due to the width of the forward portion of the fuselage.

Cockpit drawings and panoramic photographs taken from the pilot's position were used to extract information on window configuration and location so that the total field-of-view from the pilot's eye position could be determined. (This also applies to the copilot's eye position if the left and right fields of view are reversed.)

The field of view profile for each aircraft was plotted and is presented to give an indication of the pilot's available look angles. (See Figures 1 thru 8.) This profile varies somewhat from craft to craft, but the relative distribution is about the same. These plots were made from information taken from cockpit drawings, and approximations were used in some cases where the window edges were slightly curved. A composite curve was constructed to show the maximum values. (See Figure 9.) It is interesting to note the reduction in available vertical field (approximately $\pm$ 15^{o}) when looking out the cross-body side. Every aircraft surveyed is included within this plot. [a]

[a] Except overhead windows on B-52, Figure 7.



C-5 AIRCRAFT

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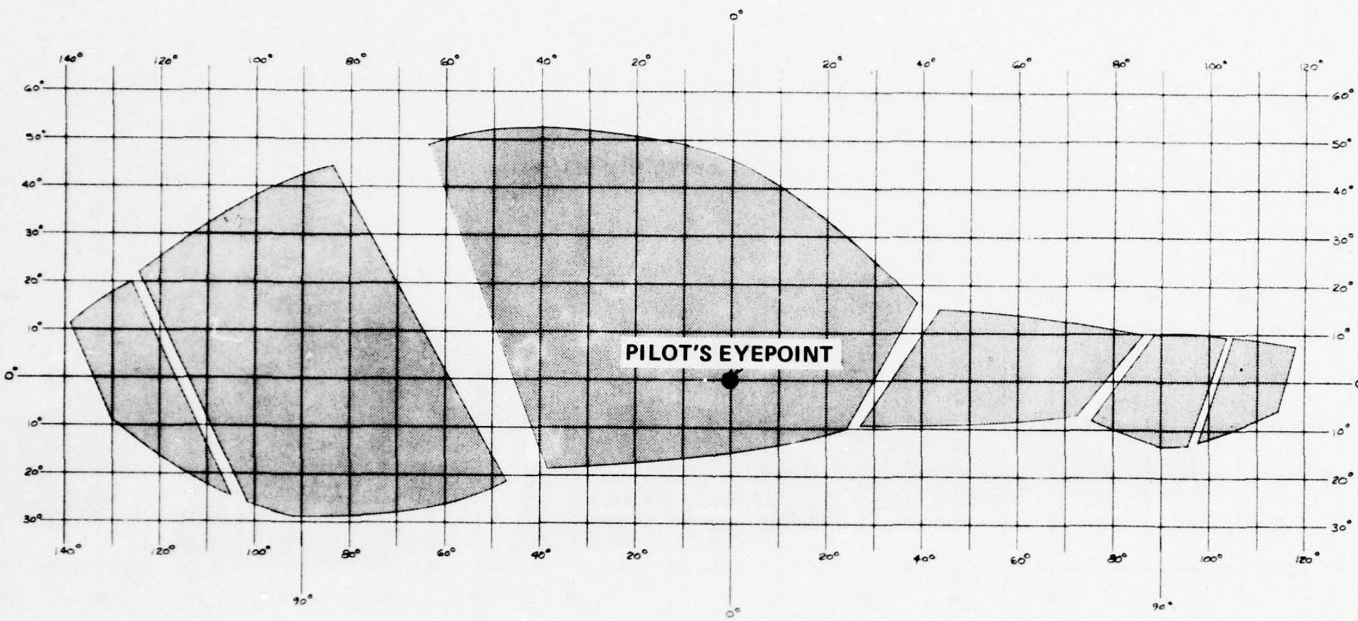
Figure 1. Field Of View From The Pilot's Position: C-5



DC-10 AIRCRAFT

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Figure 2. Field Of View From The Pilot's Position: DC-10

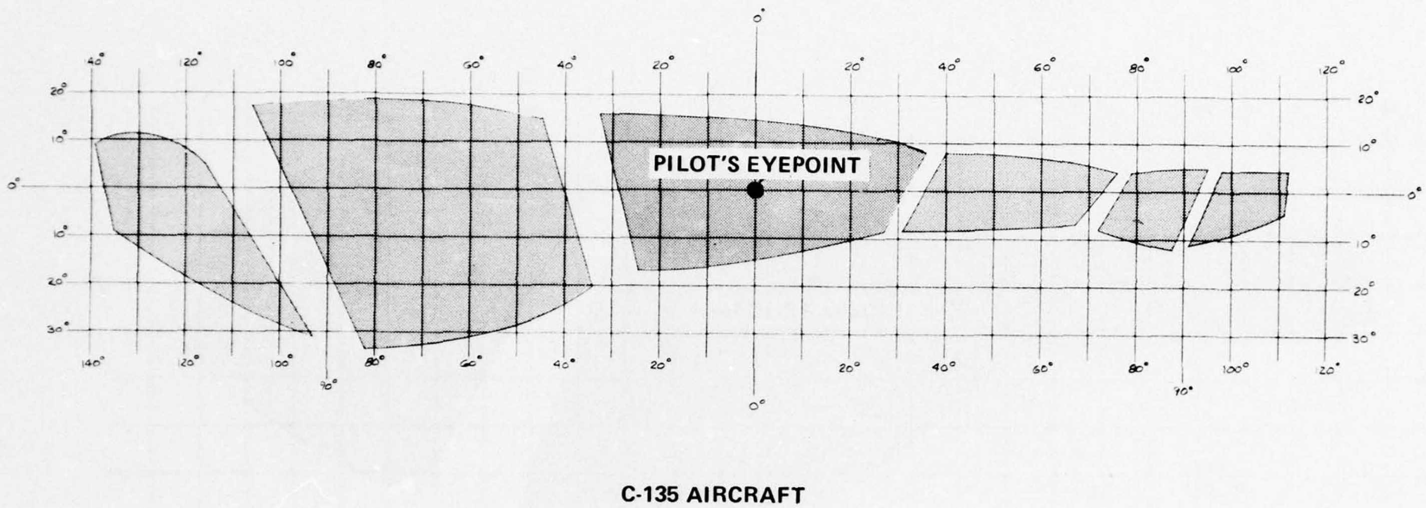

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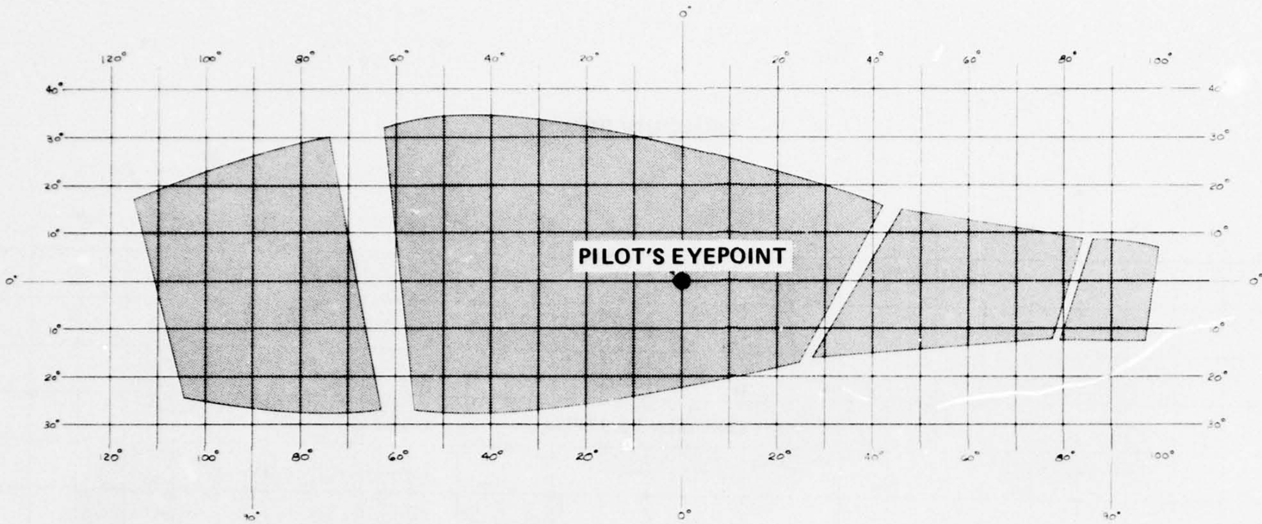
Figure 3. Field Of View From The Pilot's Position: C-135



L-1011 AIRCRAFT

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Figure 4. Field Of View From The Pilot's Position: L-1011

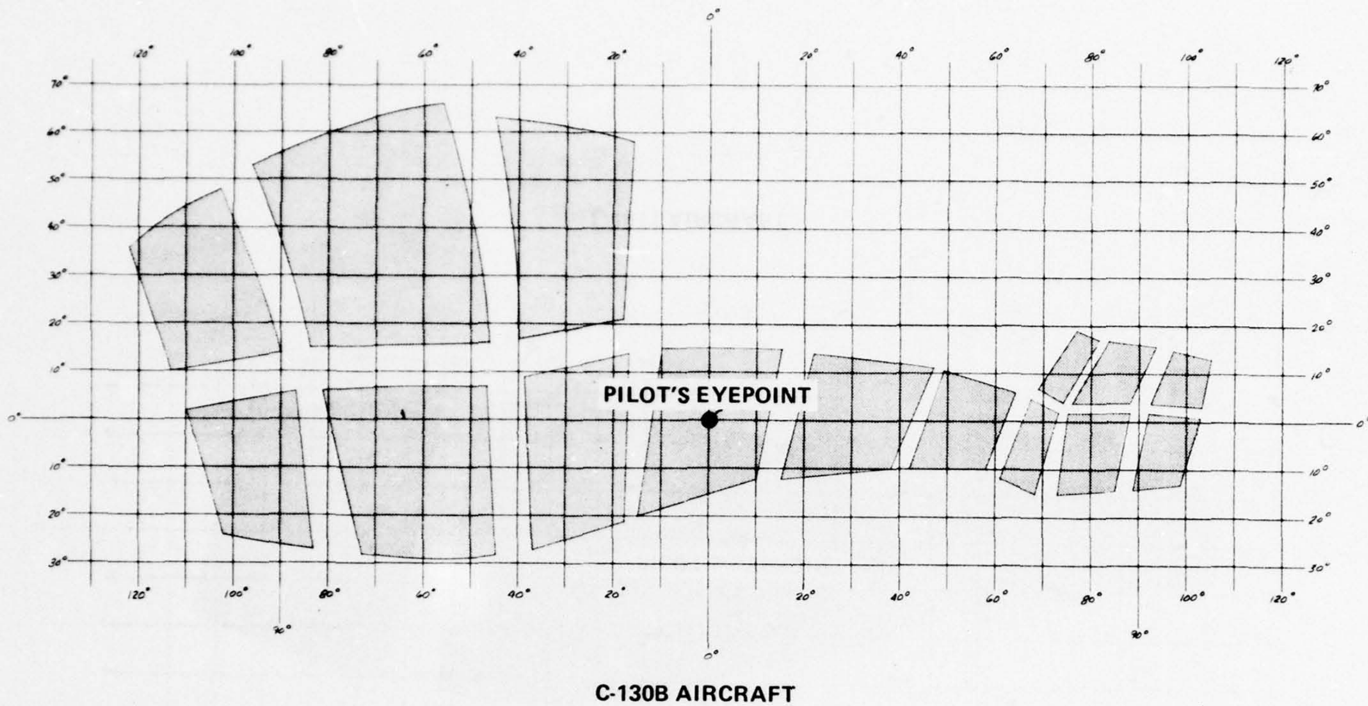

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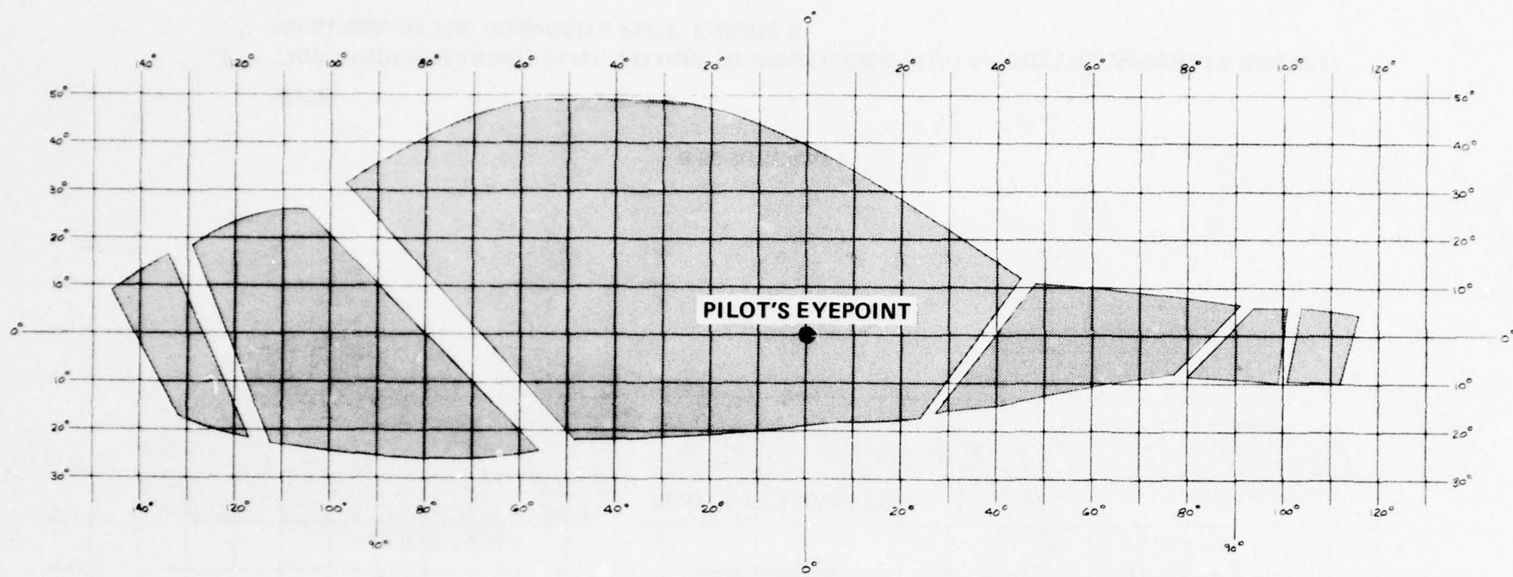
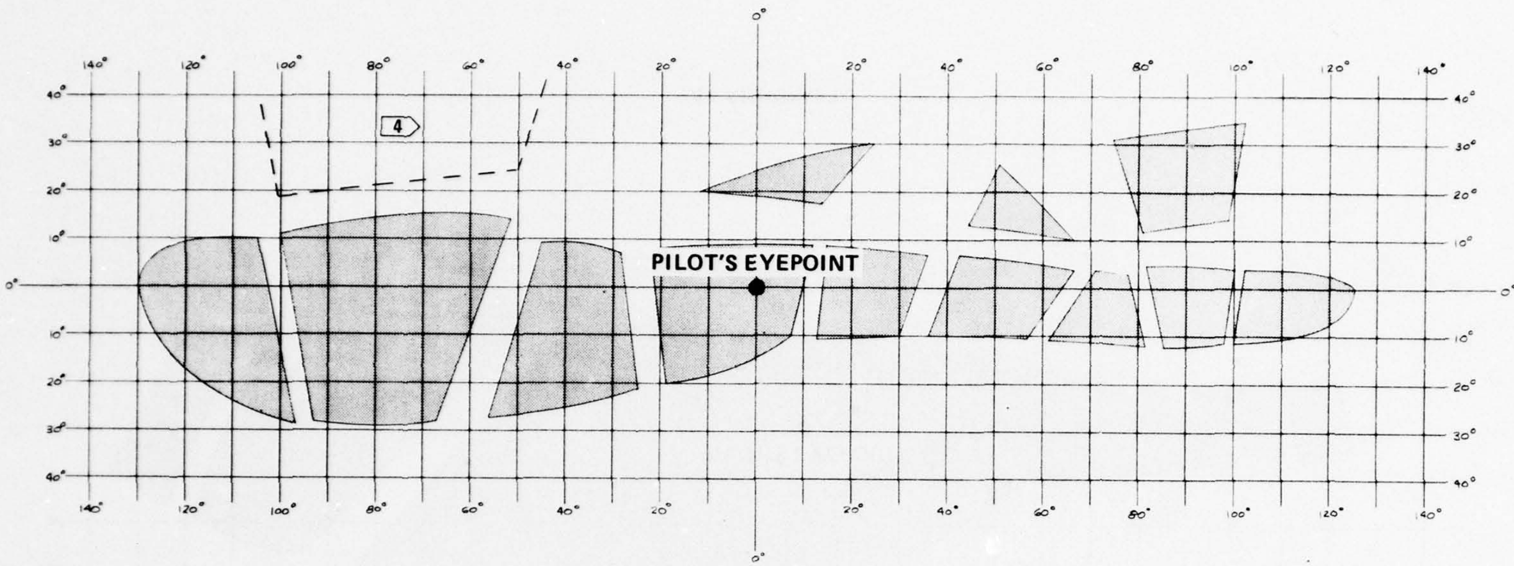
Figure 5. Field Of View From The Pilot's Position: C-130B



747 AIRCRAFT

14-655-15

Figure 6. Field Of View From The Pilot's Position: 747



B-52 AIRCRAFT

NOTE:

4 THIS WINDOW WAS NOT PLOTTED DUE TO INSUFFICIENT DATA, AND THIS AIRCRAFT WAS NOT INCLUDED IN THE COMPOSITE PLOT, FIGURE 9.

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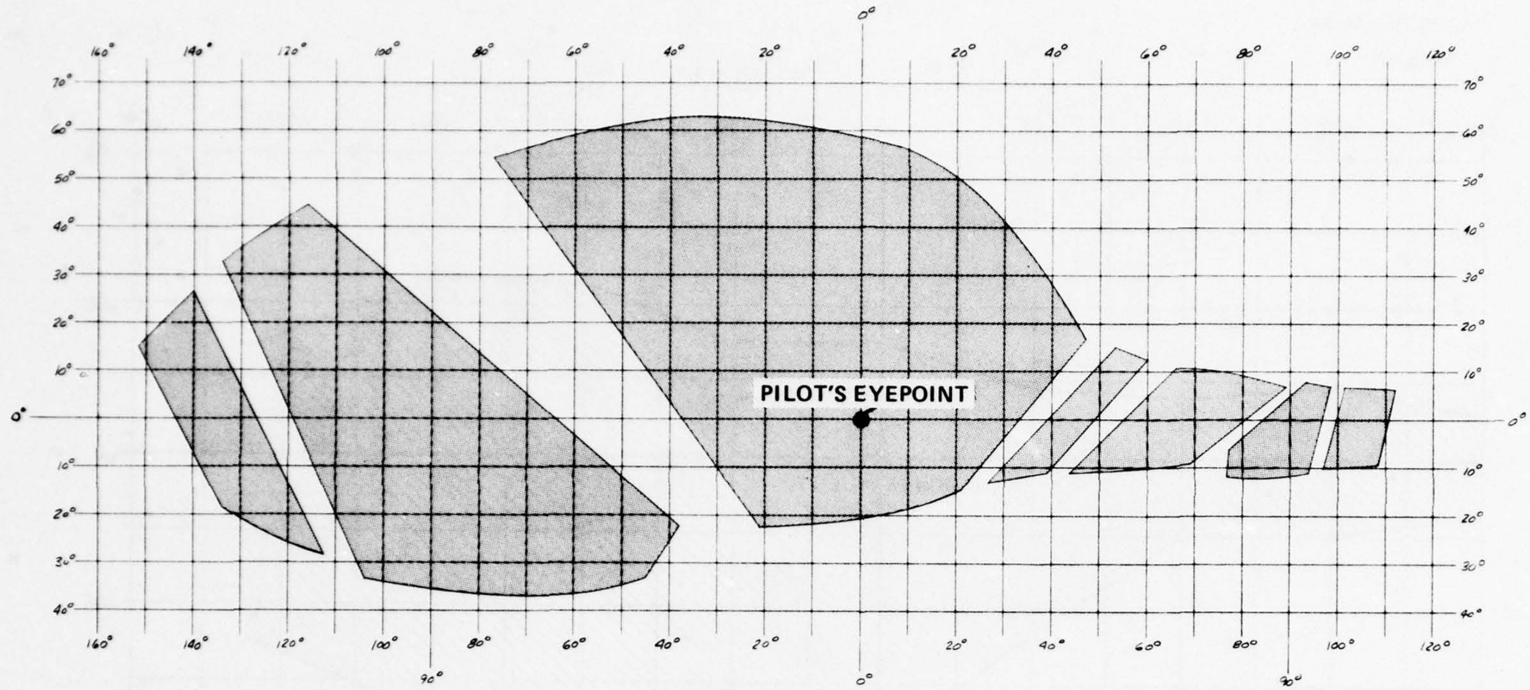
Figure 7. Field Of View From The Pilot's Position: B-52



C-141 AIRCRAFT

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Figure 8. Field Of View From The Pilot's Position: C-141

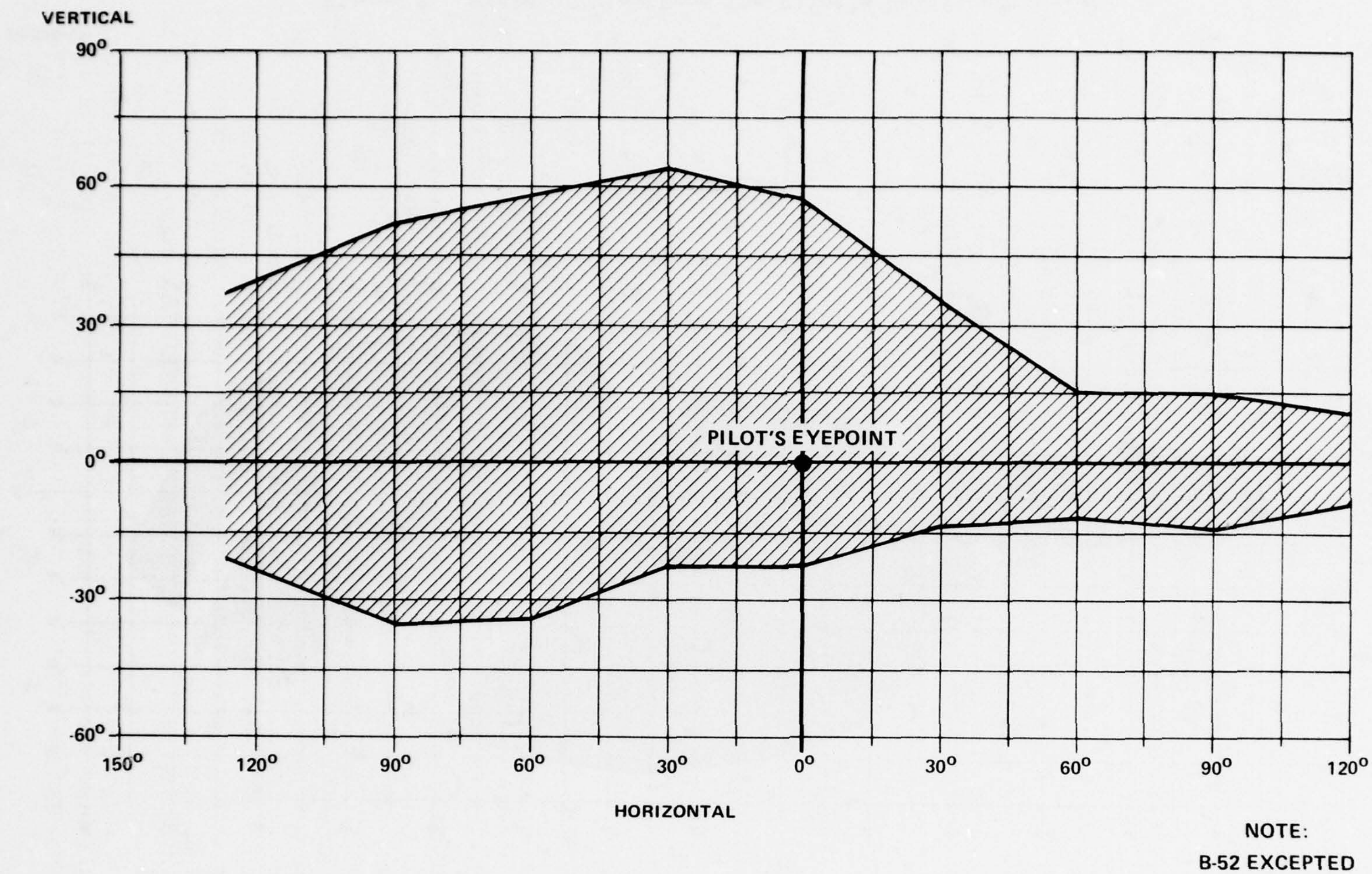

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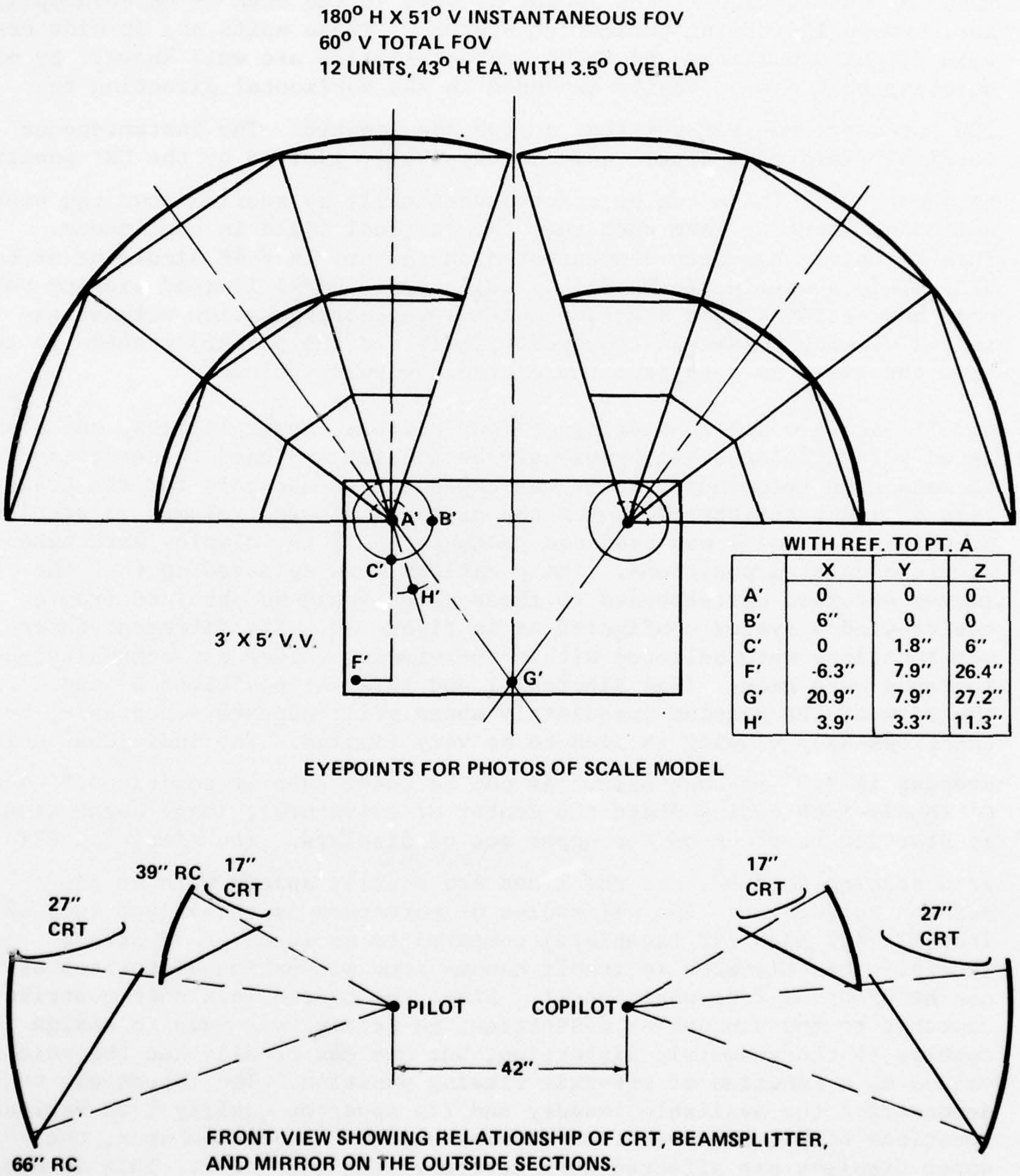
Figure 9. Composite Field Of View From The Pilot's Position

4. DISPLAY SYSTEM SYNTHESIS

4.1 CRT-Beamsplitter; On-Axis Reflective

MDEC has done a significant amount of work in the area of CRT-beamsplitter, non-pupil-forming reflective systems. These units are in wide use with flight simulators and their characteristics are well known. By mosaicking they can be easily extended in the horizontal direction to 180^{o} or more; however vertical angles are limited. The instantaneous vertical field of a single unit is physically limited by the CRT position to about 29^{o}. These can be stacked vertically by scaling down the upper units and mounting them such that the vertical field is continuous. This technique has been demonstrated on the no. 18 F-4E simulator at Luke AFB. This system performs fairly well over a small limited viewing volume; however, for this study, a multiviewer configuration with an extended viewing volume is required. Therefore the primary concern is to show the views as seen from the extended viewing volume.

A 3.7:1 scale model consisting of four mirrors, beamsplitters, and simulated CRT faceplates has previously been built and used to demonstrate the stacking techniques; so it was expedient to use this for the evaluation of image registration over the extended viewing volume. A section of this scale model was used and photographs of the display were taken at precalculated positions. The positions were selected so that the images obtained corresponded to those which would be obtained from a twelve-window system configured as in Figure 10. Six different observer locations were selected within the viewing volume and composite photographs were made. (See Figures 11 and 12.) At positions B' and C', the view of the display immediately ahead still appears acceptable, but the cross-body viewing is seen to be very limited. The individual unit overlap is 3.5^{o} on each side. As can be seen, even at positions B' and C' (a six-inch radius about the center of curvature), image separation is starting to occur on the upper set of displays. The simulated CRT grid spacing is 3.5^{o}, and the lines are equally spaced with no pincushion correction. The CRT radius of curvature is equivalent to a 40.7 inch RC, (27 inch CRT faceplate) compared to an ideal of 33 inches (RC/2). This mismatch in itself causes some pincushion distortion as can be observed from position A'. Since the camera lens does contribute somewhat to the pincushion distortion, no attempt was made to assign numbers to the geometric distortion, but one can readily see the relative values as a function of off-axis viewing position. The intent was to demonstrate the available imagery and its apparent quality from various locations within the specified viewing volume. As can be seen, the upper displays are affected more severely than the lower. This is due to the shorter RC mirrors (39 inches) and Figures 13 and 14 show the general relationship. In Figure 13, one can see that as the eye position is moved from the RC to point P, the off-axis angle (θ) is different for the upper and lower mirrors. The apparent image movement across



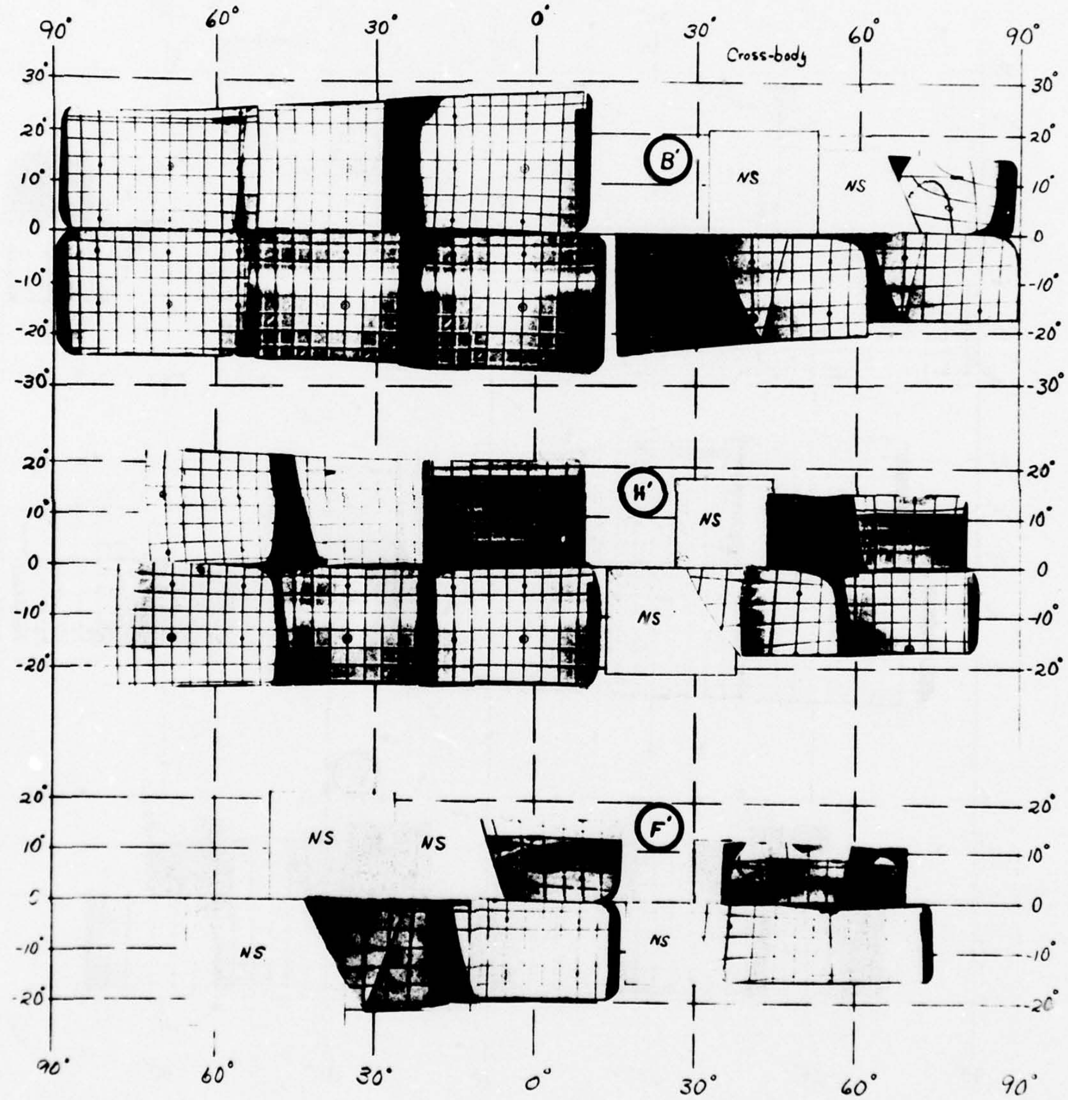
WITH REF. TO PT. A

	X	Y	Z
A'	0	0	0
B'	6"	0	0
C'	0	1.8"	6"
F'	-6.3"	7.9"	26.4"
G'	20.9"	7.9"	27.2"
H'	3.9"	3.3"	11.3"

14-655-1

Figure 10. Locations Corresponding To Photographic Evaluation Points

SEE FIGURE 10 FOR EYE LOCATION OF B', H', F'

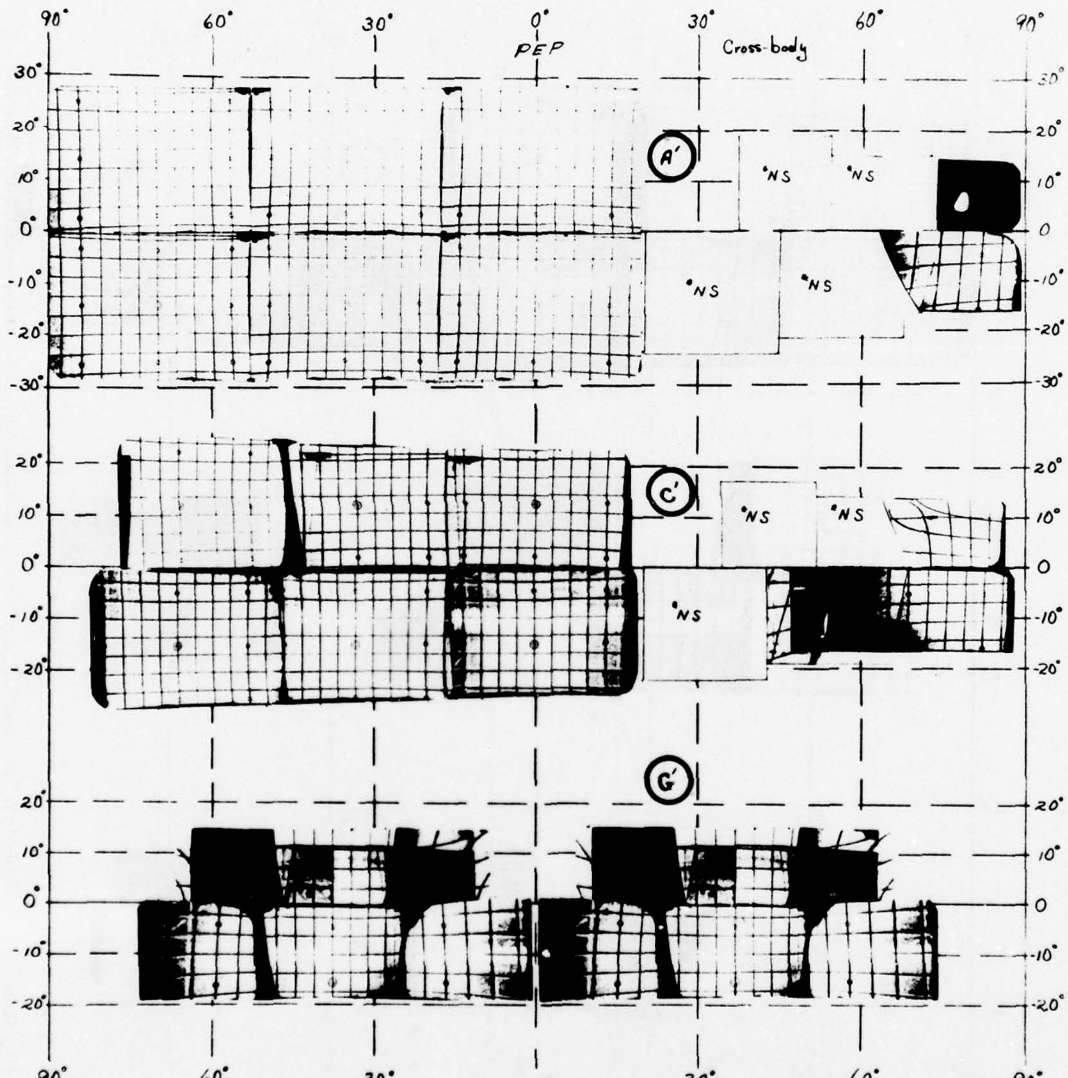


*NS – No Scene

14-655-8
(1215-1287)

Figure 11. The Display As Seen From Respective Eye Positions--12-Window System Virtual Image; Spherical Mirrors; Mosaicked

SEE FIGURE 10 FOR EYE LOCATION OF A', C', G'



*NS – No Scene

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Figure 12. The Display System As Seen From Respective Eye Positions--12 Window System Virtual Image; Spherical Mirrors; Mosaicked

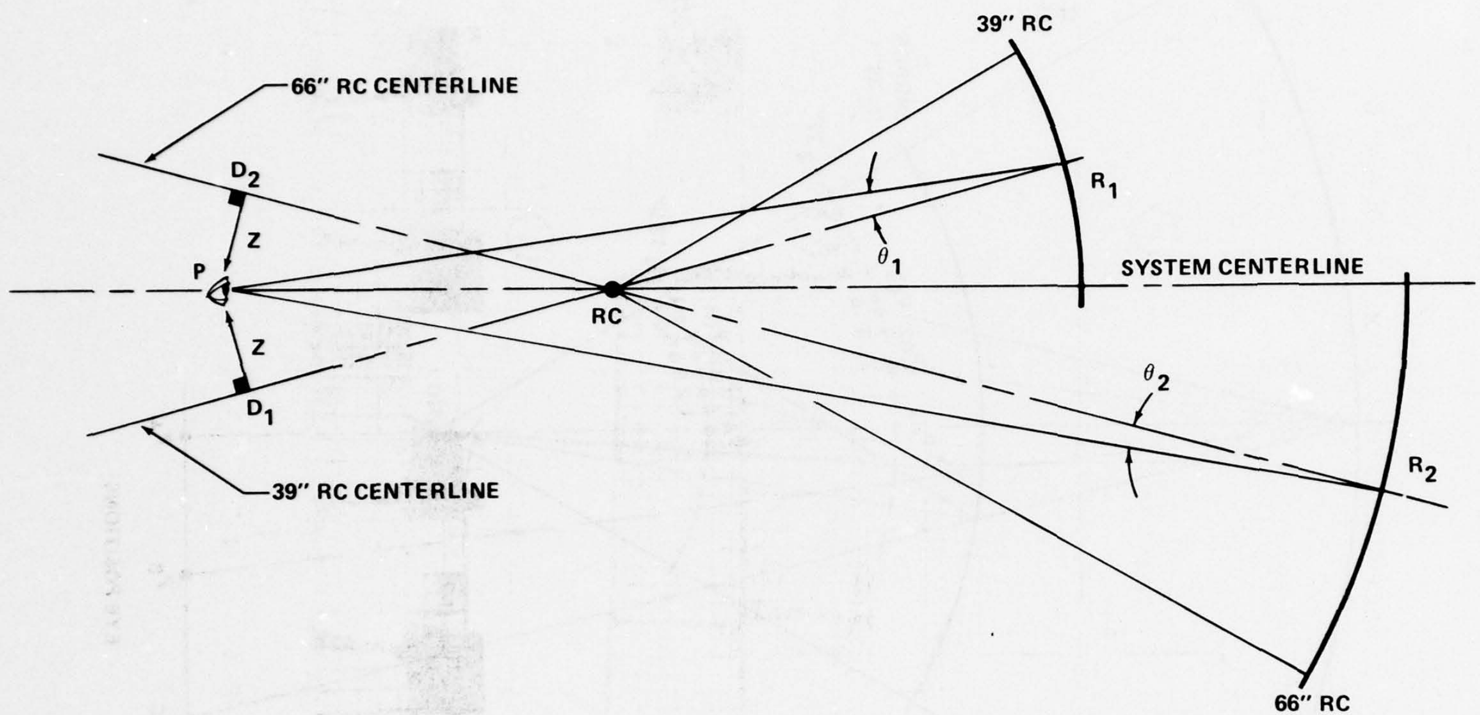

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Figure 13. Two-Mirror Vertical Stack Showing Different Radius Mirrors

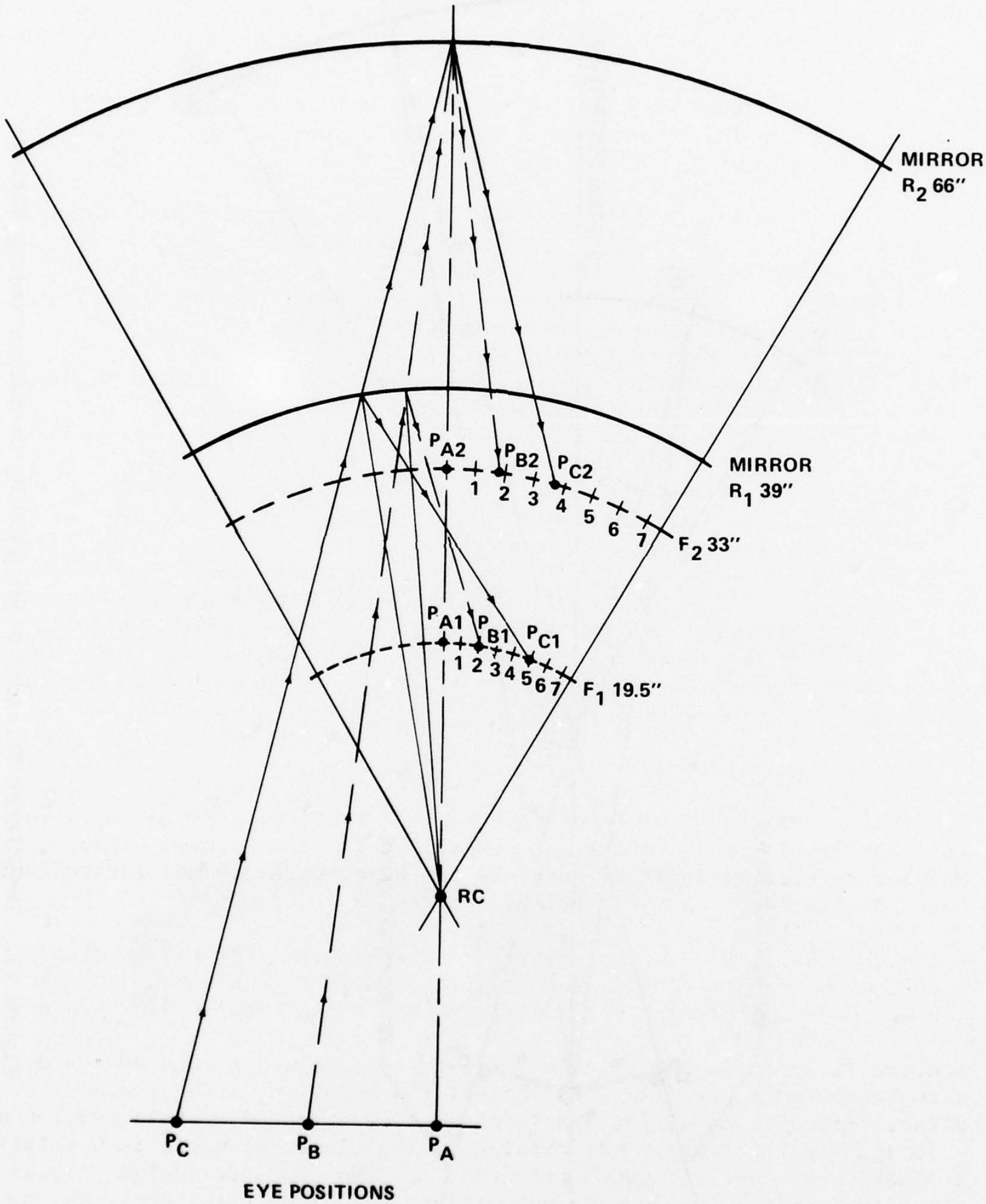

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Figure 14. Apparent Image Shift Due To Head Motion (Plan View)

the display mirror is a function of θ. Therefore, the apparent motion of the upper image (shorter RC) is greater than the lower image. This same effect applies in the horizontal plane for off-axis viewing. Figure 14 shows the same effect, by following the CRT or focal plane intercepts of rays from points P_A, P_B, and P_C, one can see that the apparent relative image motion is greater on the shorter RC display. As might be expected, this causes a misalignment of the upper and lower displays; therefore, a continuous vertical line would appear to be offset at the intersection for off-axis viewing.

The primary contributor (mirror focal surface shift) of image distortion and collimation error for off-axis viewing is shown by the ray trace in Figure 15. As the eye position moves off-axis, the optimum focal surface (CRT face position), changes location and shape, which effects a change in magnification and image location (collimation errors).

It can be concluded that a reflective system made up of individual units mosaicked together to get the required field of view is not an acceptable system for a multiviewer configuration. This is primarily due to the restricted viewing volume of such a system. At distances greater than a few inches from the system center of curvature, image separation occurs and the distortion and collimation errors become unacceptable.

It was concluded that on-axis reflective units mosaicked together would not meet the specification requirements. Image separation at the intersections and geometric distortion become severe when veiwed from more than a few inches off-axis. The off-axis collimation errors were not calculated; however, past experience shows that they would be considerably greater than the specified limits.

4.2 Refractive Systems

A refractive system capable of covering the required field of view for this application must consist of several sections mosaicked together. Modular refractive units or sections can be compared to modular reflective units as discussed in the previous section.

A limited analysis of a representative wide-angle refractive system at WPAFB, Ohio was performed. Each section consists of a single acrylic lens element with two aspheric surfaces and a flat projection screen.

Section 3, which is the pilot's forward view, Figure 16 was analyzed using computer raytracing with the pilot's position as the evaluation point. Six viewing directions (angles) were selected in this section and a design figure of merit was obtained. The figure of merit is a relative indication of overall system performance. The computer design program minimizes optical errors such as collimation, distortion, etc., as selected by the designer. It gives a computed value, associated with each error. These individual values can then be added together and a

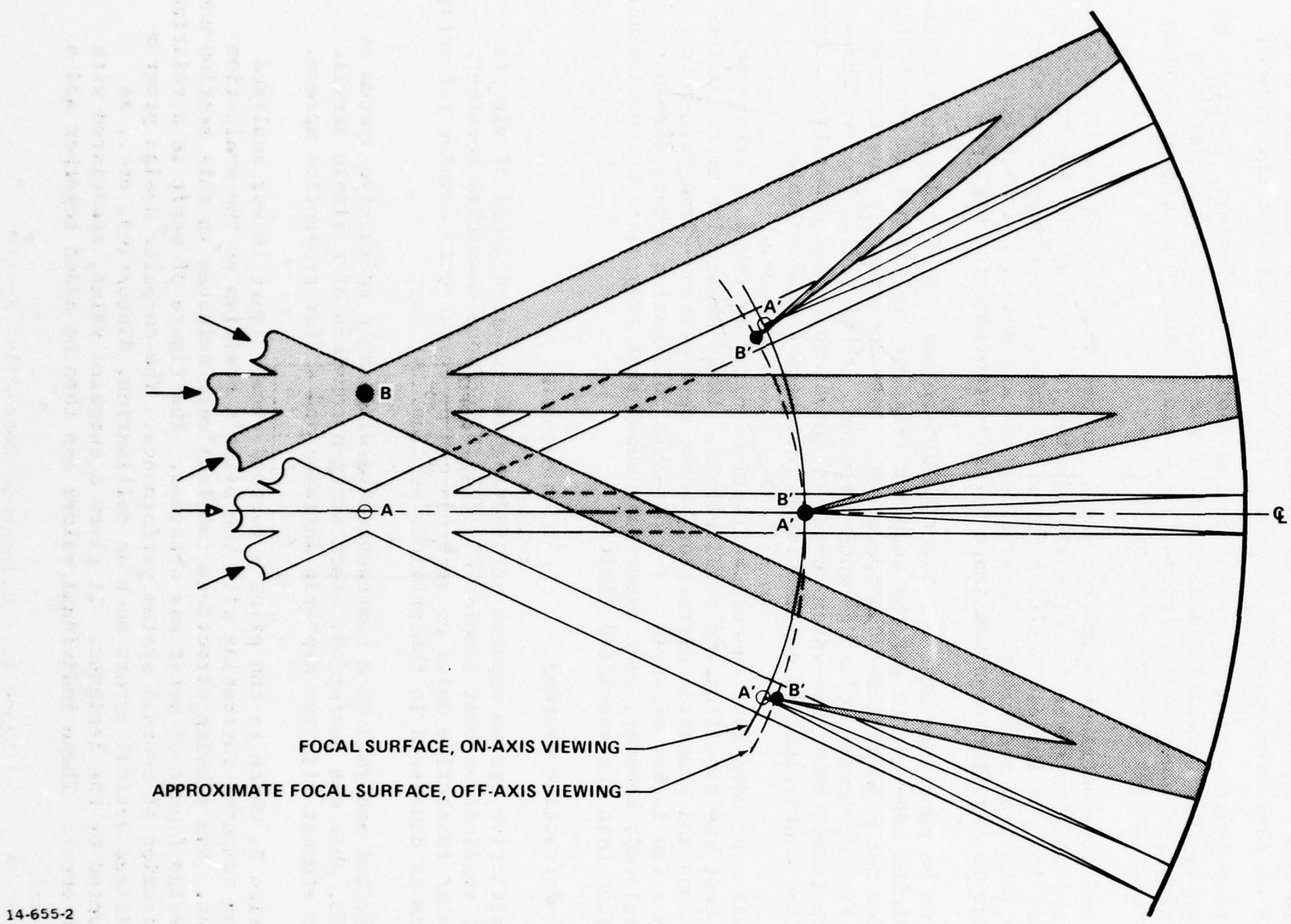
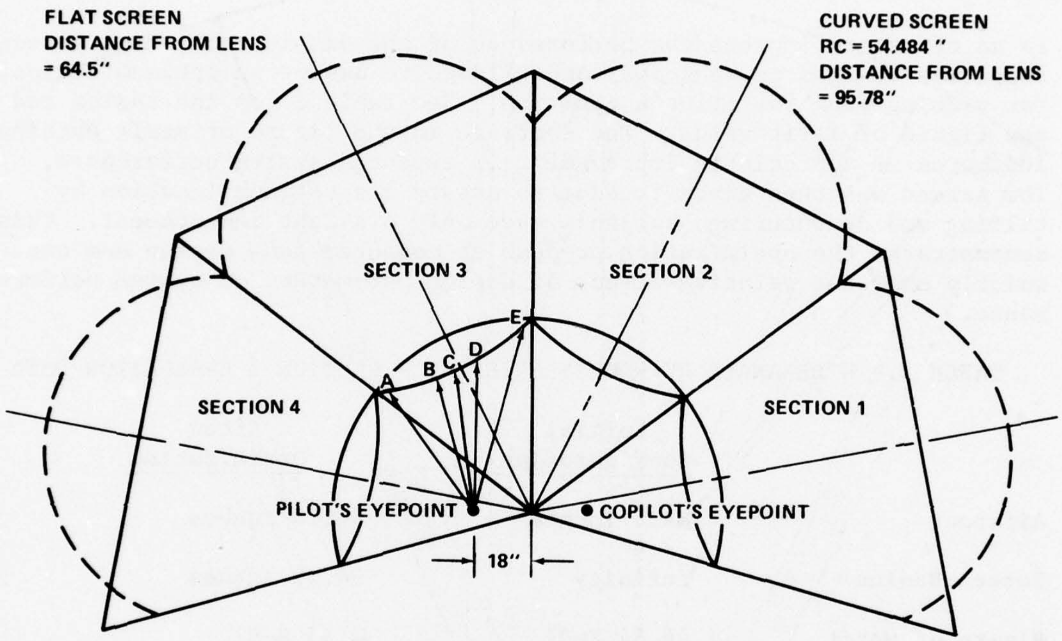


Figure 15. Raytrace Showing Focal Surface Shift



EVALUATION POINTS
ANGLES FROM
PILOT'S EYEPOINT

	VERT	HORIZ
A	0°	-40°
B	0°	-20°
C	±20°	-10°
D	0°	0°
E	0°	16.5°

14-655-32

Figure 16. Wide-Angle Refractive System

single number obtained which is commonly called the figure of merit. This gives the designer a quick indication of expected performance without having to go through a detailed evaluation run each time a parameter is changed. For example, if the screen shape is changed, then the figure of merit will change, indicating an expected improvement or degradation in performance.

In an effort to improve the performance of the display, the flat screen shape was changed to spherical and allowed to assume an optimum radius, for viewing from the pilot's position. See Table 2 for the radius and new figure of merit value. The decrease in the figure of merit obtained indicates an appreciable improvement in expected system performance. The screen was then given freedom to assume its optimum location by tilting and decentering, but this gave only a slight improvement. This demonstrates the optimization process of computer lens design and can quickly show the relative effect of design parameters on system performance.

TABLE 2. WIDE-ANGLE REFRACTIVE DISPLAY - SECTION 3 EVALUATION DATA

	Initial Configuration	After Optimization
Airspace	64.5 inches	95.78 inches
Screen Radius	Infinity	54.48 inches
Figure of Merit	46.54 E-01	4.15 E-01
Tilt (Rotation)	0^{o}	4.74^{o} in X-Z plane
Centering	0 inch	1.66 inches in X direction
Figure of Merit (After Tilt & Centering)		3.77 E-01

NOTE: This is only an optimization for the pilot's position and his view through Section 3. The copilot's view through this same window was not considered or evaluated, consequently it is not known what his view into this section would now be. It might even be worse than before.

The next step was to select a matrix of points on the screen (each point separated by 20 inches). Rays were traced from those points to the pilot's eye position. Three wavelengths were used (0.4861, 0.5876, and 0.6563 microns) to obtain collimation data and an indication of color separation. (See data Table 3). The 0.5876-micron line collimation data were plotted in Figure 17 to show approximate values of divergence and convergence.

Table 3. Collimation and Range Data (Section 3)

	VERTICAL	SCREEN POINTS	HORIZONTAL -20″ CONV (-) DIV (+)	HORIZONTAL -20″ DIPVERGENCE	HORIZONTAL 0″ CONV (-) DIV (+)	HORIZONTAL 0″ DIPVERGENCE	HORIZONTAL +20″ CONV (-) DIV (+)	HORIZONTAL +20″ DIPVERGENCE	HORIZONTAL +40″ CONV (-) DIV (+)	HORIZONTAL +40″ DIPVERGENCE
COLLIM DATA IN DEGREES	+40″	D	—	—	-0.069°	0.218°	0.172°	0.070°	—	—
		F	—	—	-0.082°	0.201°	0.148°	0.068°	—	—
		C	—	—	-0.061°	0.224°	0.182°	0.071°	—	—
	+20″	D	-0.124°	0.141°	0.232°	0.022°	0.256°	0.046°	-0.362°	0.087°
		F	-0.107°	0.118°	0.215°	0.023°	0.241°	0.046°	-0.349°	0.088°
		C	-0.129°	0.150°	0.240°	0.020°	0.263°	0.045°	-0.368°	0.087°
	0″	D	-0.325°	0.0	0.268°	0.0	0.275°	0.0	-0.350°	0.0
		F	-0.367°	0.0	0.254°	0.0	0.260°	0.0	-0.338°	0.0
		C	-0.307°	0.0	0.274°	0.0	0.281°	0.0	-0.354°	0.0
	-20″	D	-0.124°	0.141°	0.232°	0.022°	0.256°	0.046°	-0.362°	0.087°
		F	-0.107°	0.118°	0.215°	0.023°	0.241°	0.046°	-0.349°	0.088°
		C	-0.129°	0.150°	0.240°	0.020°	0.263°	0.045°	-0.368°	0.087°
	-40″	D	—	—	-0.069°	0.218°	0.172°	0.070°	—	—
		F	—	—	-0.082°	0.201°	0.148°	0.068°	—	—
		C	—	—	-0.061°	0.224°	0.182°	0.071°	—	—
COLLIM (RANGE) DATA IN FEET	+40″	D	—	—	-172.99	54.76	69.40	170.52	—	—
		F	—	—	-145.57	59.39	80.65	175.54	—	—
		C	—	—	-195.68	53.29	65.59	168.12	—	—
	+20″	D	- 96.26	84.66	51.45	542.57	46.63	259.49	-32.97	137.20
		F	-111.56	101.16	55.52	518.98	49.53	259.49	-34.20	135.64
		C	- 92.53	79.58	49.74	596.85	45.39	265.26	-32.44	137.20
	0″	D	- 36.73	∞	44.54	∞	43.41	∞	-34.10	∞
		F	- 32.52	∞	46.99	∞	45.91	∞	-35.32	∞
		C	- 38.88	∞	43.56	∞	42.48	∞	-33.72	∞
	-20″	D	- 96.26	84.66	51.45	542.57	46.63	259.49	-32.97	137.20
		F	-111.56	101.16	55.52	518.98	49.53	259.49	-34.20	135.64
		C	- 92.53	79.58	49.74	596.83	45.39	265.26	-32.44	137.20
	-40″	D	—	—	-172.99	54.76	69.40	170.52	—	—
		F	—	—	-145.57	59.39	80.65	175.54	—	—
		C	—	—	-195.68	53.29	65.59	168.12	—	—

WAVELENGTH D = 0.5876M F = 0.4861M C = 0.6563M M = MICRONS

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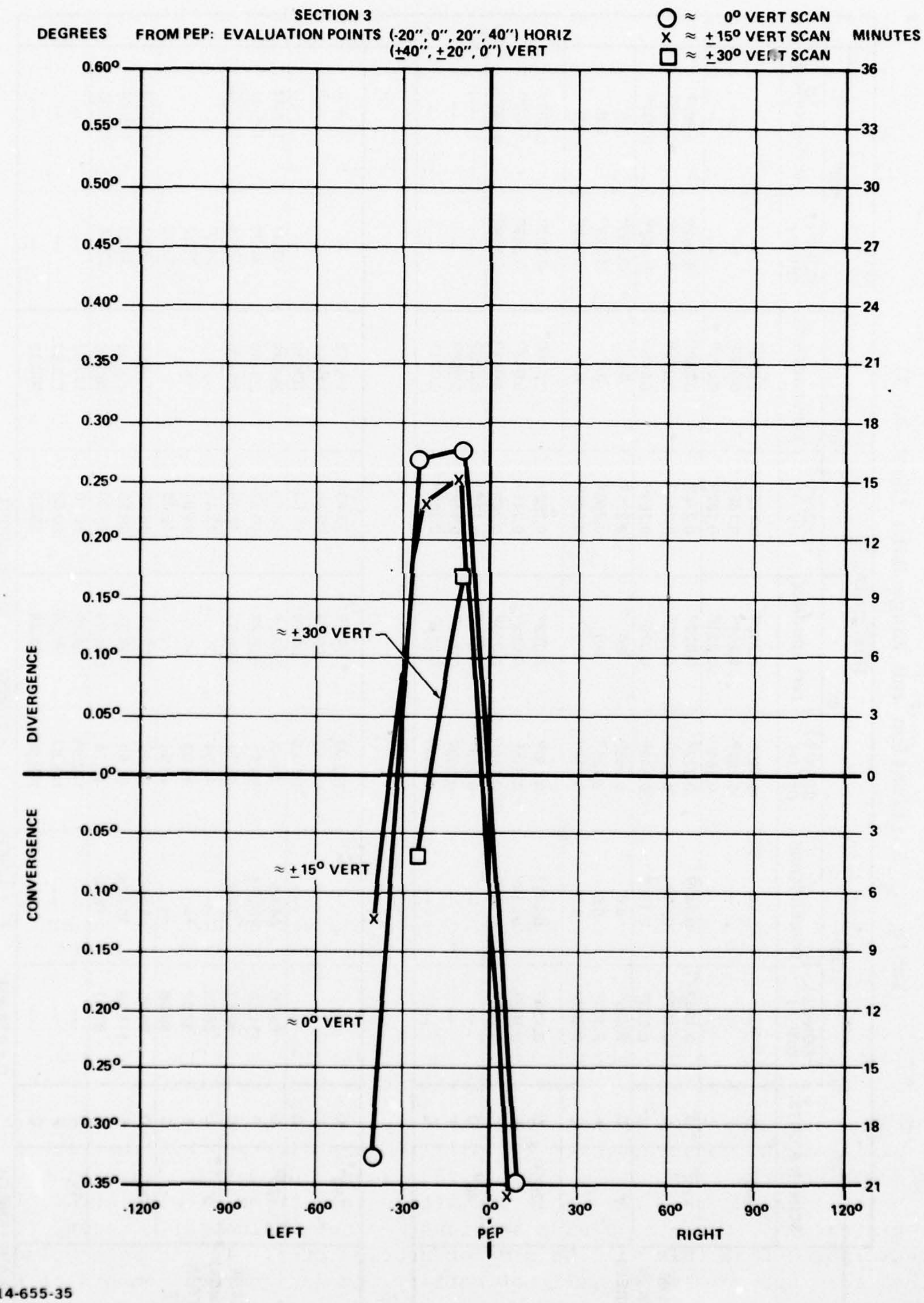

Figure 17. Section 3, Collimation Data

Ray angles from the inter-ocular point at the nominal eye position, from each screen point, were tabulated (Table 4) and plotted (Figure 18) to show the geometric distortion or image nonlinearity. The plots show that both the collimation errors and distortion values are quite severe. (Convergence errors greater than 6 milliradians and distortions greater than 22%) (see Area "A", Figure 18).

TABLE 4. ANGULAR POSITION DATA FROM PILOT'S EYEPOINT (SECTION 3)

DATA TABLE

	-40"	-20"	0"	+20"	+40"	+60"
+40"		38.21°L 32.7°UP	25.21°L 32.03°UP	8.95°L 28.9°UP	7.95°L 29.07°UP	
+20"		39.88°L 18.6°UP	23.96°L 15.43°UP	9.60°L 14.27°UP	4.66°R 13.63°UP	19.52°R 13.73°UP
0	49.04°L 0	38.84°L 0	23.91°L 0	9.77°L 0	4.25°R 0	21.30°R 0
-20"	47.87°L 17.83°DN	39.88°L 18.6°DN	23.96°L 15.43°DN	9.60°L 14.27°DN	4.66°R 13.63°DN	19.52°R 13.73°DN
-40"		38.21°L 32.70°DN	25.21°L 32.03°DN	8.95°L 28.90°DN	7.95°R 29.07°DN	

L = Left

R = Right

Rays were traced from designated points on the screen and the angles shown represent the direction the pilot would have to look in order to see the point in question.

This system is fairly representative of wide-angle refractive systems and illustrates the general characteristics of viewing a refractive system from off-axis positions. This analysis shows that collimation errors within the forward 45° horizontal field (prime viewing area) ranged from 6 milliradians convergence to 4.7 milliradians divergence. The rate of change was very sharp over this limited field. Geometric distortions greater than 20% were also observed within this prime viewing area. Image registration between adjoining sections was not evaluated; however, it is anticipated that this will be a major problem area. It can be concluded that this type of system will not satisfy the design requirements of this study.

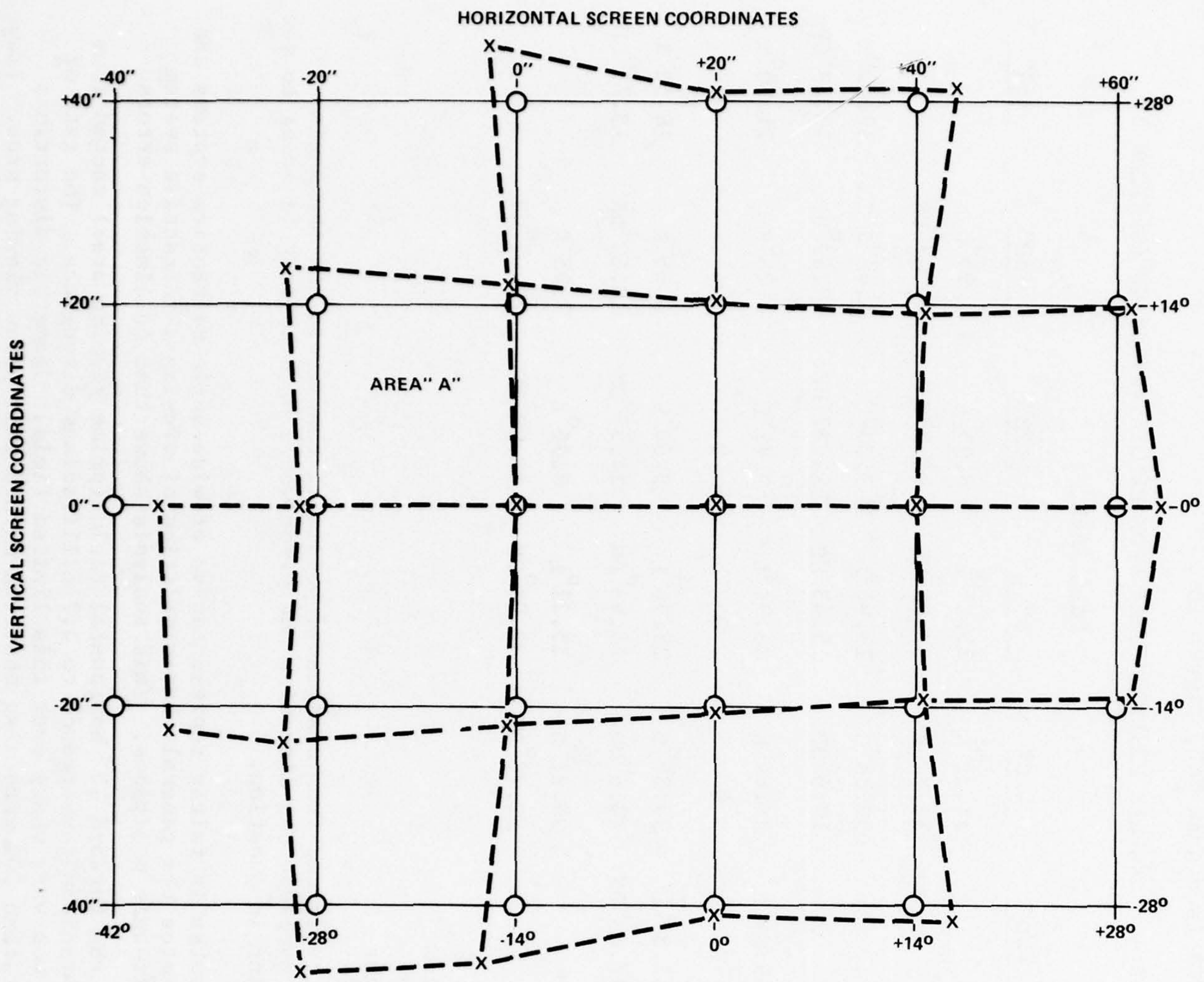

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Figure 18. Section 3, Distortion And Linearity Plot--The Dashed Lines Show How The Square Gridwork Appear To The Pilot

Lenses are fundamentally uniaxial devices and are subject to increasingly severe limitations when used in a noncentered manner. There are several statements that can be made about reflective and refractive systems in general and are presented in Table 5.

The system technique that we believe has the highest possibility of meeting the given requirements is an off-axis reflective system. It is attractive because extended horizontal angles (up to 360^{o}) and large vertical fields (60^{o} - 70^{o}) can be achieved without mosaicking; and long radius of curvature mirrors can be used to give a large viewing volume with acceptable characteristics. Such a system is analyzed and presentted in the next section.

TABLE 5. COMPARISON OF GENERAL CHARACTERISTICS -- REFLECTIVE AND REFRACTIVE SYSTEMS

Reflective; On-Axis CRT-Beamsplitter-Mirror	Refractive; In-Line CRT-Lens System
1) Speeds down to f/.5 easily obtained at moderate expense.	Speeds down to about f/1.5 easily attained designs to f/1.0 only with great difficulty and expense. Multielement designs required.
2) System resolution is not limited by the mirror, and no color correction is required.	Special design effort is required to obtain sufficient resolution and color correction. With lenses it is more difficult to obtain acceptable range and dipvergence values over the required FOV and viewing volume.
3) Distance from mirror surface to the pilot can equal the RC of the mirror. A large diameter is required to cover a large FOV.	About 50" is required in most aircraft between the pilot and the first element. This dictates a large diameter lens to cover a large field of view.
4) Light weight mirrors can be used.	Fast, large diameter, multielement lenses are heavy whether made of glass or plastic.
	Fresnel lenses suffer from light scattering from the grooves and sides. The effect is visually disturbing, especially in night scenes, and very difficult to remove.
5) Large viewing volumes require large diameter mirrors with long RC.	Large exit pupils or large viewing volumes require large

TABLE 5 COMPARISON OF GENERAL CHARACTERISTICS -- REFLECTIVE AND REFRACTIVE SYSTEMS (CONT)

	Reflective; On-Axis CRT-Beamsplitter-Mirror	Refractive; In-Line CRT-Lens System
		diameter lenses with long focal lengths.
6)	The natural input surface is convex - same direction as CRT radius.	The natural input surface is concave - opposite direction of CRT radius. Correction for field curvature is an added complexity in the design.
7)	Vertical instantaneous FOV mechanically limited to 28^o -30^o.	Vertical instantaneous FOV only limited by lens characteristics.
8)	Beamsplitter reduces the optical efficiency to 25%.	No beamsplitter - Not as much CRT brightness required.
9)	Horizontal mosaicking relatively easy, but difficulty in stacking more than 2 units vertically.	Both horizontal and vertical mosaicking relatively easy but lenses must be cut to rectangular or pentagonal shape.
10)	Viewing volume is limited for mosaicked systems - image separation occurs with head motion.	Same limitations as mirrors, but more severe due to the lens element thickness and off-axis aberrations.

5. OFF-AXIS REFLECTIVE SYSTEM PROPERTIES

5.1 Off-Axis System Configuration

To meet the extended field of view requirements without the limitations previously discussed for modular systems, we selected an off-axis reflective system. This system consists of a large wrap-around mirror and screen, with a light valve projection system to supply the input image. Since both the screen and mirror can be made continuous, there will be no variable image discontinuities in the display. Three or four projectors will be used to supply the total scene with edge-registered images. A large viewing volume can be obtained by using a long radius mirror.

5.2 Selected System Design

A 132 inch radius of curvature mirror was selected and tilted back at 22.5^{o} to allow off-axis viewing. This was chosen on the basis of previous experience in off-axis reflective systems. This is a compromise to obtain the characteristics of a long radius of curvature system without the system becoming too unwieldy physically.

5.2.1 Design and Optimization for Central Design Point. The ACCOS V optical computer design program (owned and licensed by Scientific Calculations, Inc., Rochester, N.Y.) was used to design, optimize, and evaluate various combinations of mirror and screen shapes. A brief conceptual description of the design and evaluation technique is as follows:

Several sets of rays at selected angles are traced from the design position to the mirror. After reflection, the convergence points are all used to best fit a selected screen shape (spherical, toroidal, etc.). For collimation evaluation runs, sets of rays are then traced in reverse from the screen intersection points back to the design position, and their angles noted. Each set of rays consists of a chief (or nose) ray, a left eye ray and a right eye ray. (See Figure 19).

The initial design and optimization runs were made with the observer fixed on a vertical line through the radii of curvatures of the mirror and screen at a distance of 120 inches from the mirror surface. As required by the ACCOS V program the design angles for conic and high-order aspheric systems were restricted to $\pm 60^{o}$ in the horizontal plane. The system designs were made by means of a progressive series of design and optimization runs, each having more freedom in selecting the optimum curve shape for the mirror and screen. The parameters used for optimization were collimation (range--image focus point) and dipvergence (vertical angular deviation between the rays that strike the left and right eyes) errors.

One set of optimization runs was made with just collimation (Δx or Δz)

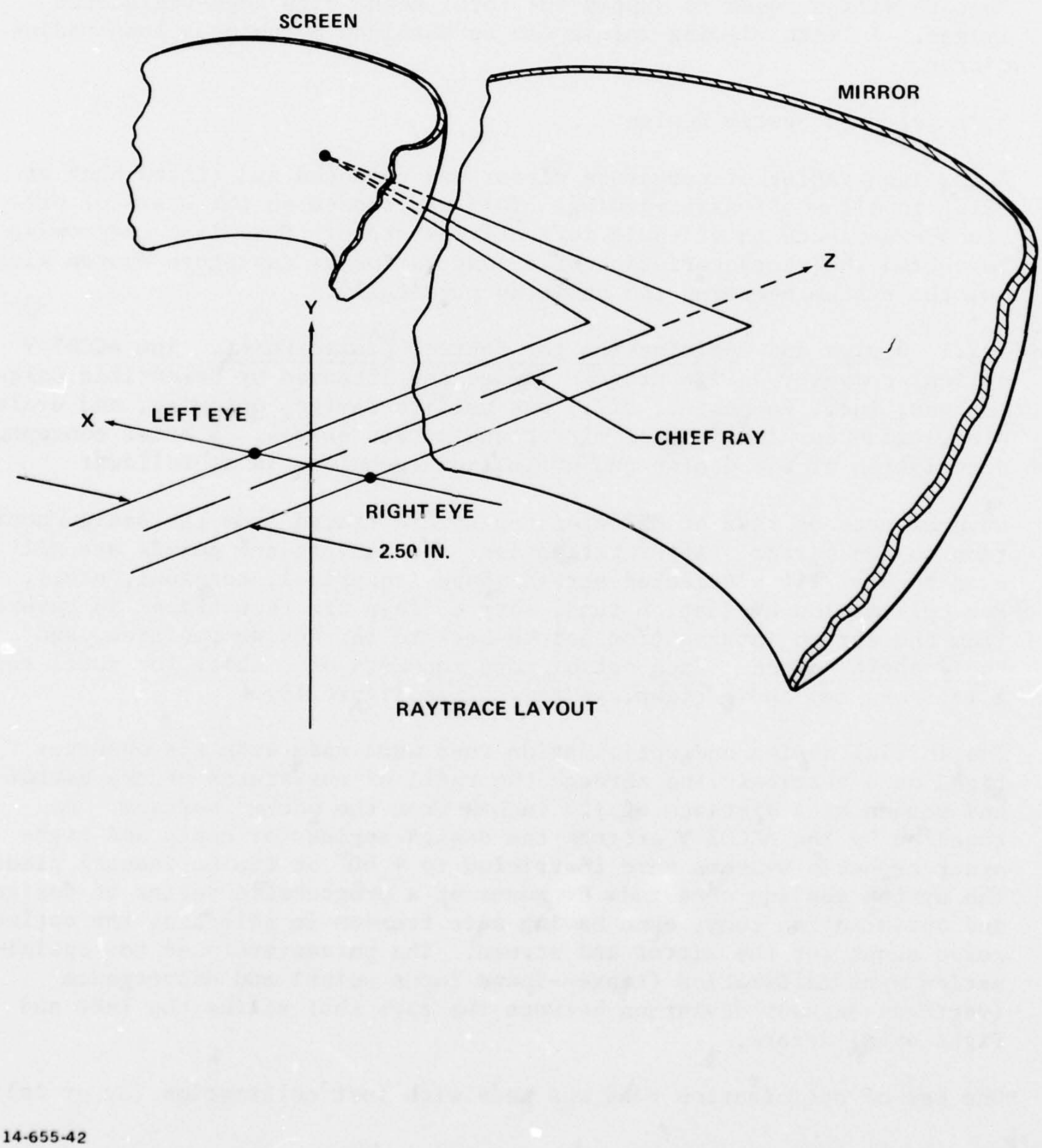

Figure 19. Design Ray Orientation

errors as the controlling factor. Another set of runs was made with both collimation (Δx or Δz) and dipvergence (Δy) errors as controlling factors. Most configurations have had two or more optimization runs with different controlling parameters. The following combinations have been designed and optimized for minimum range and dipvergence errors. See Table 6 for figure of merit values.

5.2.2 Comparison of Shape Combinations. Mirror and screen shape have a significant effect as can be seen from the design data values in this table. For example, the figure of merit value for a Spherical Mirror Spherical Screen (SMSS) went from 35.4 E-04 down to (28.8 E-06) for a Spherical Mirror Toroidal Screen (SMTS) which is more than two orders of magnitude, which would constitute a large improvement in performance. Thus by changing from a spherical to a toroidal screen a tremendous gain was made. However beyond this, the improvement with system complexity was not nearly as dramatic; in fact, some more complex configurations were found to be less effective.

5.3 Evaluation at Design Eye Point

Evaluation runs were made to obtain collimation data on designs no. 9 (SMTS), and no. 1 (SMSS) and are plotted in Figure 20. As was expected there is a significant improvement of the toric screen system over the spherical screen system when evaluated on the system center (on a vertical line passing through the radii of curvatures).

5.4 Evaluation at PEP - Optimized at Design Center

The SMTS was then evaluated at the pilot's eye point without reoptimizing the design for that off-axis position and the collimation data are presented in Figure 21. The curves show that the rays are convergent; this happens because the design was not optimized at that position. Note scale differences between Figures 20 and 21. The next step was to re-optimize the design for this off-axis position.

Table 6. Wide-Angle Optimized Design Data for Center of Design Viewing

NO.	HORIZ DESIGN ANGLE	DESIGN CONFIGURATION AND NAME	FIGURE OF MERIT	NO.	HORIZ DESIGN ANGLE	DESIGN CONFIGURATION AND NAME	FIGURE OF MERIT
1	± 60°	SMSS1Ø3	35.4E-04	16	± 60°	TMAYTSXY	16.4E-05
2	± 60°	SMSSXY	37.5E-04	17	± 60°	TMAXTS3	41.2E-05
3	± 60°	SMKS1Ø3	33.9E-04	18	± 60°	AYTMTS3	27.0E-06
4	± 60°	KMKS1Ø3	19.7E-04	19	± 60°	AYTMTSXY	17.1E-05
5	± 60°	KMKSXY	33.6E-04	20	± 60°	AXTMTS3	73.0E-06
6	± 60°	KMKS1Ø4	17.5E-04	21	± 60°	AYTMS3	35.4E-06
7	± 60°	SMTS1Ø3	28.8E-06	22	± 60°	AYTMSXY	16.2E-05
8	± 60°	SMTSXY	14.3E-05	23	± 90°	SMSS90	45.7E-04
9	± 60°	KMTS1Ø3	14.1E-06	24	± 90°	SMSSXY9	52.7E-04
10	± 60°	TMSS1Ø3	29.0E-05	25	± 90°	KMKS90	42.0E-04
11	± 60°	TMTS1Ø3	20.0E-06	26	± 90°	KMKSXY9	48.6E-04
12	± 60°	TMTSXY	13.8E-05	27	± 120°	SMSS120	55.8E-04
13	± 60°	TMTSK3	39.7E-06	28	± 120°	SMSSXY12	66.2E-04
14	± 60°	TMTSKXY	16.2E-05	29	± 120°	KMKS120	60.0E-04
15	± 60°	TMAYTS3	34.7E-06	30	± 120°	KMKSXY12	65.6E-04

MIRROR	SCREEN	DESIGN IDENT PREFIX
SPHERICAL	SPHERICAL	SMSS
SPHERICAL	CONIC	SMKS
CONIC	CONIC	KMKS
SPHERICAL	TOROIDAL	SMTS
CONIC	CONIC-TORIDAL	KMTS
TORIC	SPHERICAL	TMSS
TORIC	TORIC	TMTS
CONIC-TOROIDAL	CONIC-TOROIDAL	TMTSK
CONIC-TOROIDAL	HI-ORDER ASPH. "Y" TOROIDAL	TMAYTS
CONIC-TOROIDAL	HI-ORDER ASPH. "X" TOROIDAL	TMAXTS
HI-ORDER "Y" TOROIDAL	CONIC-TOROIDAL	AYTMTS
HI-ORDER ASPH. "X" TOROIDAL	CONIC-TOROIDAL	AXTMTS
HI-ORDER ASPH. "Y" TOROIDAL	HI-ORDER ASPH. "Y" TOROIDAL	AYTMS

THE SMALLER THE FIGURE OF MERIT VALUE THE BETTER IS THE EXPECTED PERFORMANCE
EXAMPLE: NO. 9 FIGURE OF MERIT = 28.8×10^{-6}, NO. 1 FIGURE OF MERIT = 35.4×10^{-4}, BETTER PERFORMANCE WOULD BE EXPECTED FROM NO. 9.

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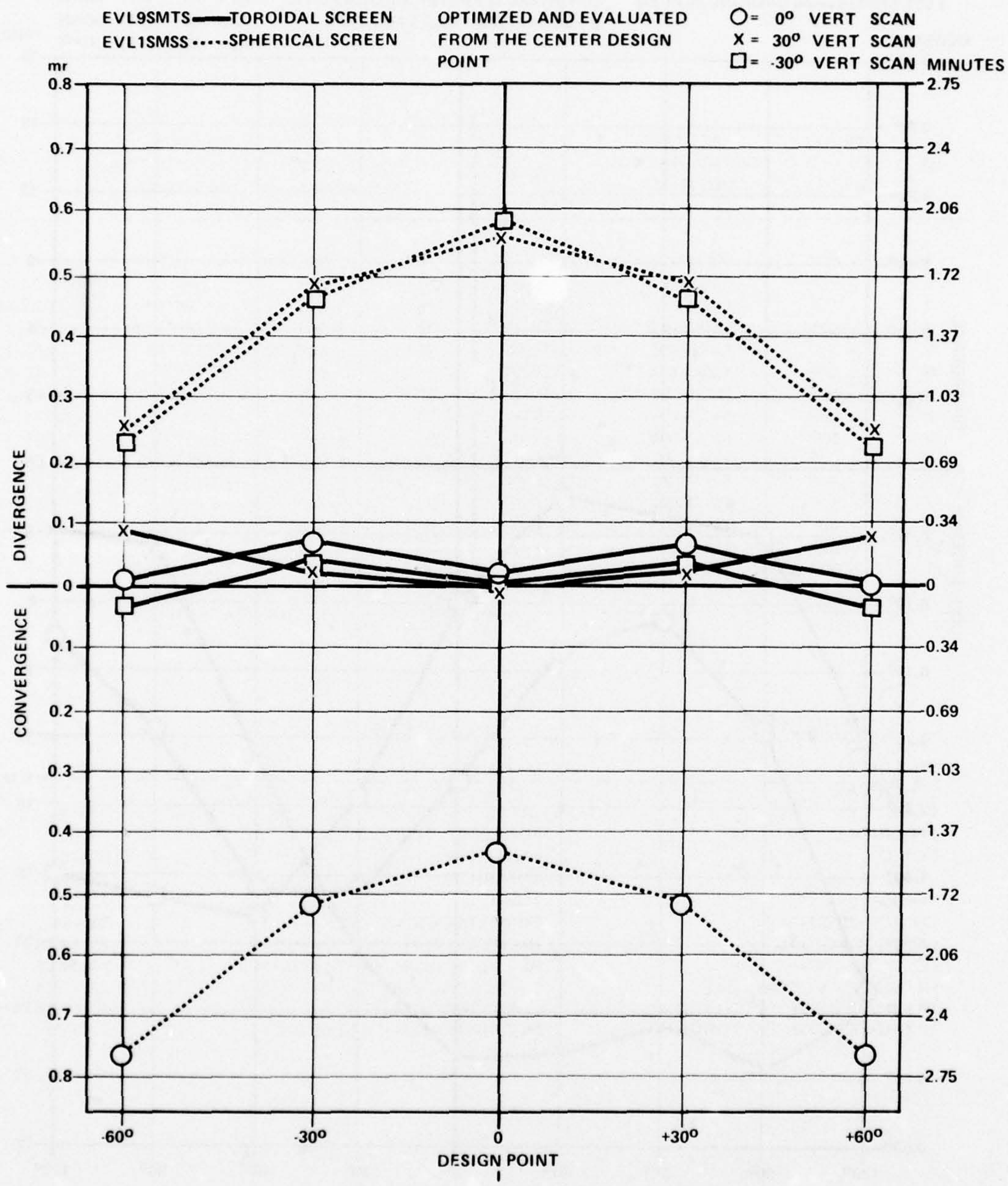

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Figure 20. Collimation Curves From Design Center

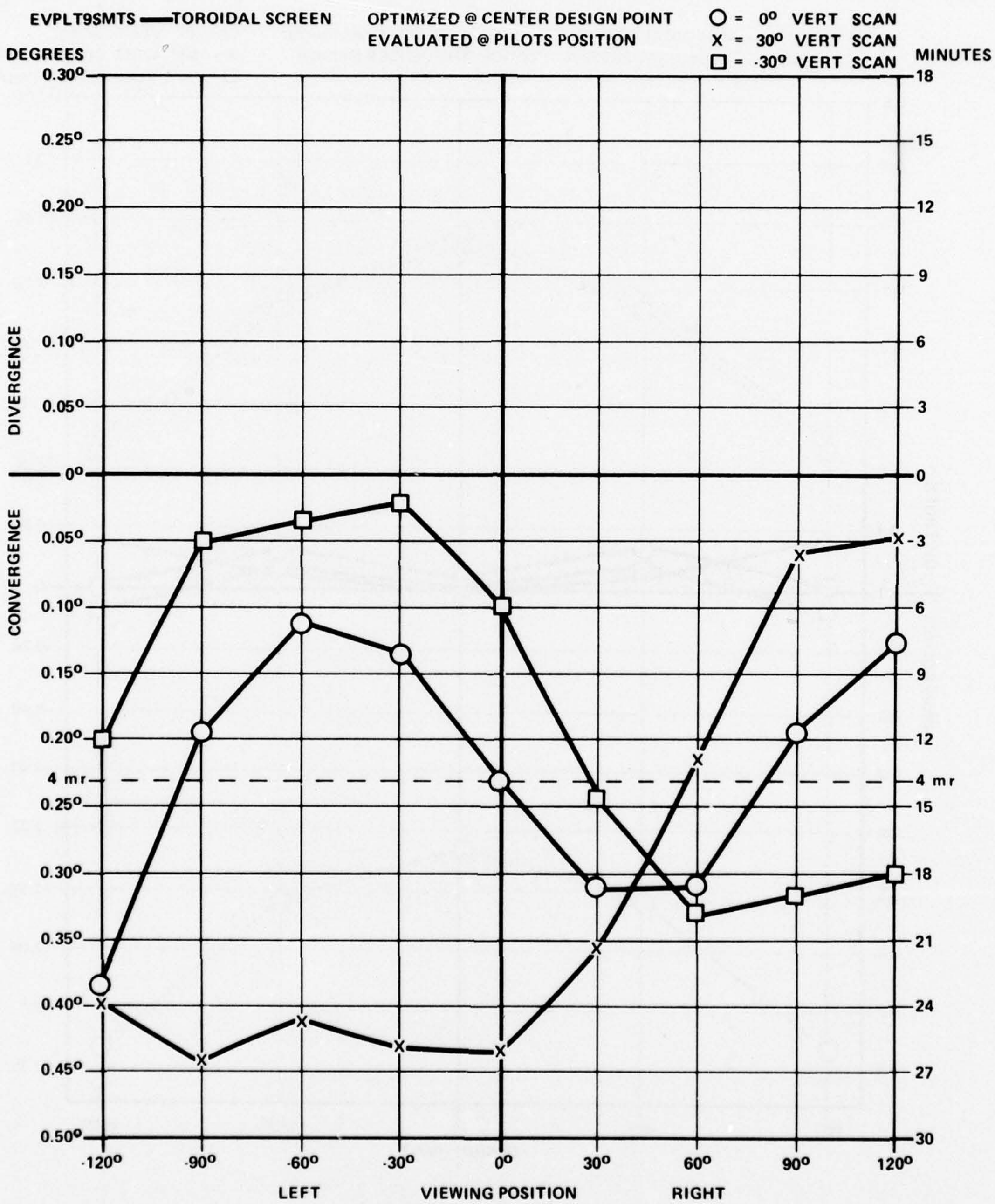

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Figure 21. Collimation Curves Spherical Mirror, Toroidal Screen

6. SELECTED WIDE FIELD SYSTEM

6.1 System Optimization and Evaluation from PEP

As a reference for comparison purposes two systems (SMSS and SMTS) were designed, optimized and evaluated. The SMTS system was chosen for the following reasons:

1. It would be fairly easy to fabricate. The toric screen could be formed relatively easily from plastic and of course the spherical mirror would present no special problem, since it could be made in sections and butted together to form a single mirror.

2. The design would be symmetrical and two 120° sections could be assembled to form a total uninterrupted horizontal field of view of 240°. This cannot be done with the conics and high-order aspherics. They must be designed and evaluated for the total field covered.

3. The previously obtained figure of merit values showed that this system had great potential.

The spherical system (SMSS) was chosen simply as a standard for comparison.

These systems were optimized from the PEP (Pilot Eye Point) over an angle of 0° to 60° in azimuth and $\pm 30^{\circ}$ in elevation. A radius of curvature axis extended through the center of the 3- by 5- by 1.5 foot viewing volume and the pilots were separated by 42 inches. The second design was made with the viewing volume (and PEP) moved up 9 inches and back 6 inches (see Figure 22). This allowed the PEP to be closer to the system radius of curvature. This necessitated changing the mirror tilt angle from 22.5° to 30° so that the 60° vertical field of view would still be available at the PEP.

6.2 Comparison of Performance Over the Viewing Volume

Various points (Figure 22) in the viewing volume were chosen and collimation (range) and dipvergence data were obtained and plotted. A 240° horizontal field of view was chosen for design and evaluation; however, it should be noted that this exceeds the 180° field of view required in the specification. The $\pm 90^{\circ}$ points on the plots can be used as end points for specification conformance.

The collimation data are plotted in ordinate units of degrees and arc-minutes with a 4-milliradian reference line to indicate the maximum desired convergence. These units can be directly converted to diopters, range--focus distance in feet, and milliradians by referring to Table 7.

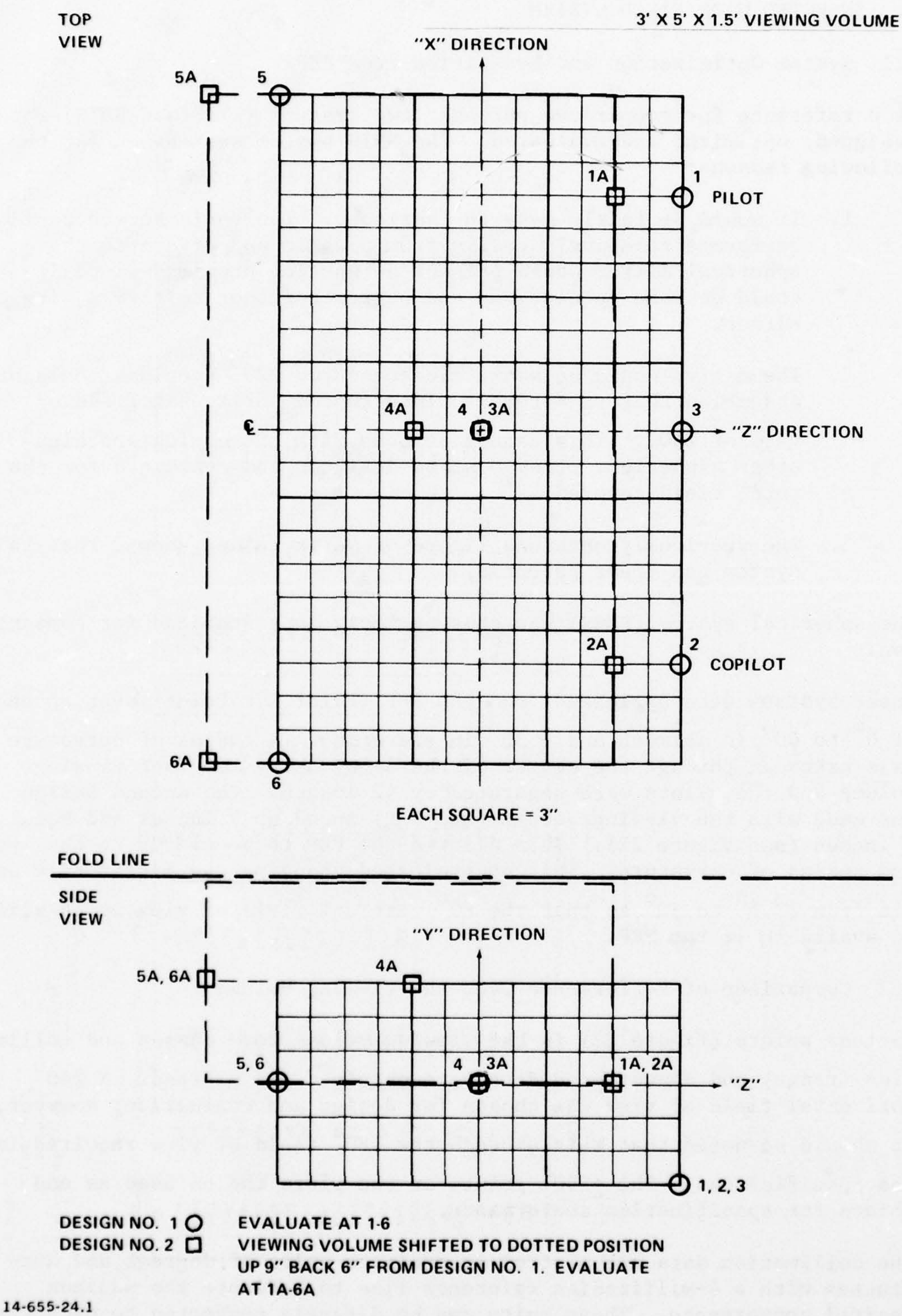
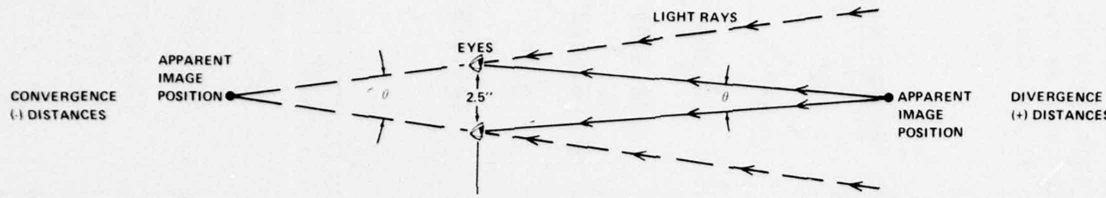


Figure 22. Evaluation Point Location

Table 7. Collimation Conversion Chart



DIVERGENCE					
DEGREES	ANGLE MINUTES	ANGLE MILLIRAD	APPARENT IMAGE POSITION (FT)	STANDARD OPTICAL DIOPTERS	PRISM DIOPTERS
0.7333	44	12.804	16.3	0.2024	1.2804
0.7000	42	12.222	17.0	0.1932	1.222
0.6667	40	11.64	17.9	0.184	1.164
0.6333	38	11.058	18.8	0.1748	1.1058
0.6000	36	10.476	19.9	0.1656	1.0476
0.5667	34	9.894	21.1	0.1564	0.9894
0.5333	32	9.312	22.4	0.1472	0.9312
0.5000	30	8.73	23.9	0.138	0.873
0.4667	28	8.148	25.6	0.1288	0.8148
0.4323	26	7.566	27.5	0.1196	0.7566
0.4000	24	6.984	29.8	0.1104	0.6984
0.3667	22	6.402	32.5	0.1012	0.6402
0.3333	20	5.82	35.8	0.092	0.582
0.3000	18	5.238	39.8	0.0828	0.5238
0.2667	16	4.656	44.8	0.0736	0.4656
0.2333	14	4.074	51.1	0.0644	0.4074
0.2000	12	3.492	59.7	0.0552	0.3492
0.1667	10	2.91	71.6	0.046	0.291
0.1333	8	2.328	89.5	0.0368	0.2328
0.0833	6	1.746	119	0.0276	0.1746
0.0667	4	1.164	179	0.0184	0.1164
0.0333	2	0.582	358	0.0092	0.0582
0.0167	1	0.291	716	0.0046	0.0291
0	0	0	∞	0	0

CONVERGENCE					
DEGREES	ANGLE MINUTES	ANGLE MILLIRAD	APPARENT IMAGE POSITION (FT)	STANDARD OPTICAL DIOPTERS	PRISM DIOPTERS
0	0	0	∞	0	0
-0.0167	-1	-0.291	-716	-0.0046	-0.0291
-0.0333	-2	-0.582	-358	-0.0092	-0.0582
-0.0667	-4	-1.164	-179	-0.0184	-0.1164
-0.0833	-6	-1.746	-119	-0.0276	-0.1746
-0.1333	-8	-2.328	-89.5	-0.0368	-0.2328
-0.1667	-10	-2.91	-71.6	-0.046	-0.291
-0.2000	-12	-3.492	-59.7	-0.0552	-0.3492
-0.2333	-14	-4.074	-51.1	-0.0644	-0.4074
-0.2667	-16	-4.656	-44.8	-0.0736	-0.4656
-0.3000	-18	-5.238	-39.8	-0.0828	-0.5238
-0.3333	-20	-5.82	-35.8	-0.092	-0.582
-0.3667	-22	-6.402	-32.5	-0.1012	-0.6402
-0.4000	-24	-6.984	-29.8	-0.1104	-0.6984
-0.4333	-26	-7.566	-27.5	-0.1196	-0.7566
-0.4667	-28	-8.148	-25.6	-0.1288	-0.8148
-0.5000	-30	-8.73	-23.9	-0.138	-0.873
-0.5333	-32	-9.312	-22.4	-0.1472	-0.9312
-0.5667	-34	-9.894	-21.1	-0.1564	-0.9894
-0.6000	-36	-10.476	-19.9	-0.1656	-1.0476
-0.6333	-38	-11.058	-18.8	-0.1748	-1.1058
-0.6667	-40	-11.64	-17.9	-0.814	-1.164
-0.7000	-42	-12.222	-17.0	-0.1932	-1.222
-0.7333	-44	-12.804	-16.3	-0.2024	-1.2804

NOTE: SUGGESTED TOLERANCES FOR BI-OCULAR VISION RAY DISPARITIES

	(ARC MINUTES) DESIRABLE	MAXIMAL
1. HORIZ. IN PLANE OF EYES		
a. CONVERGENCE	0	-10
b. DIVERGENCE	30	40
2. VERTICAL		
a. DIPVERGENCE	± 15	± 15
3. CHROMATIC ERROR	± 4	± 6

NOTE: "USE OF NON-CONVENTIONAL OPTICAL MATERIALS FOR VISUAL SIMULATION", PAPER BY DR. GOTTFRIED ROSENDAHL PRESENTED AT NAVAL TRAINING EQUIPMENT CENTER, NOV. 1973.

14-655-5

A complete set of data is presented for each of the two configurations from the selected points in the viewing volume and for each of the two designs (see Figures 23 - 30). Collimation errors at the back corners are severe but an observer from that point will not have $\pm 30^{o}$ instantaneous vertical field of view for the full 240^{o} azimuth. It should be noted that the same dipvergence curve is used for both the SMSS and the SMTS because the differences only show up in the third significant figure and is beyond the accuracy of the graphs. This happens because the "y" radius of the toric screen is nearly the same as the radius of the spherical screen. See Table 8 and Figure 31 for design data.

TABLE 8. OFF-AXIS SYSTEM DESIGN DATA

SMSS	Designation	Design No. 1	Design No. 2
Mirror Radius	R_m	132"	132"
Mirror Tilt	A	22.5^{o}	30^{o}
Screen Radius	R_x	75.3771"	78.5669"
	R_y	75.3771"	78.5669"
Decentering	B	7.66480"	6.5162"
Pilot Position	C	9"	0.0"
	D	121.9520	114.31535"
SMTS			
Mirror Radius	R_m	132"	132"
Mirror Tilt	A	22.5^{o}	30^{o}
Screen Radius	R_x	58.9657"	57.6170"
	R_y	77.6708"	80.4192"
Decentering	B	6.50786"	5.42578"
Pilot Position	C	9"	0
	D	121.9520"	114.31535"

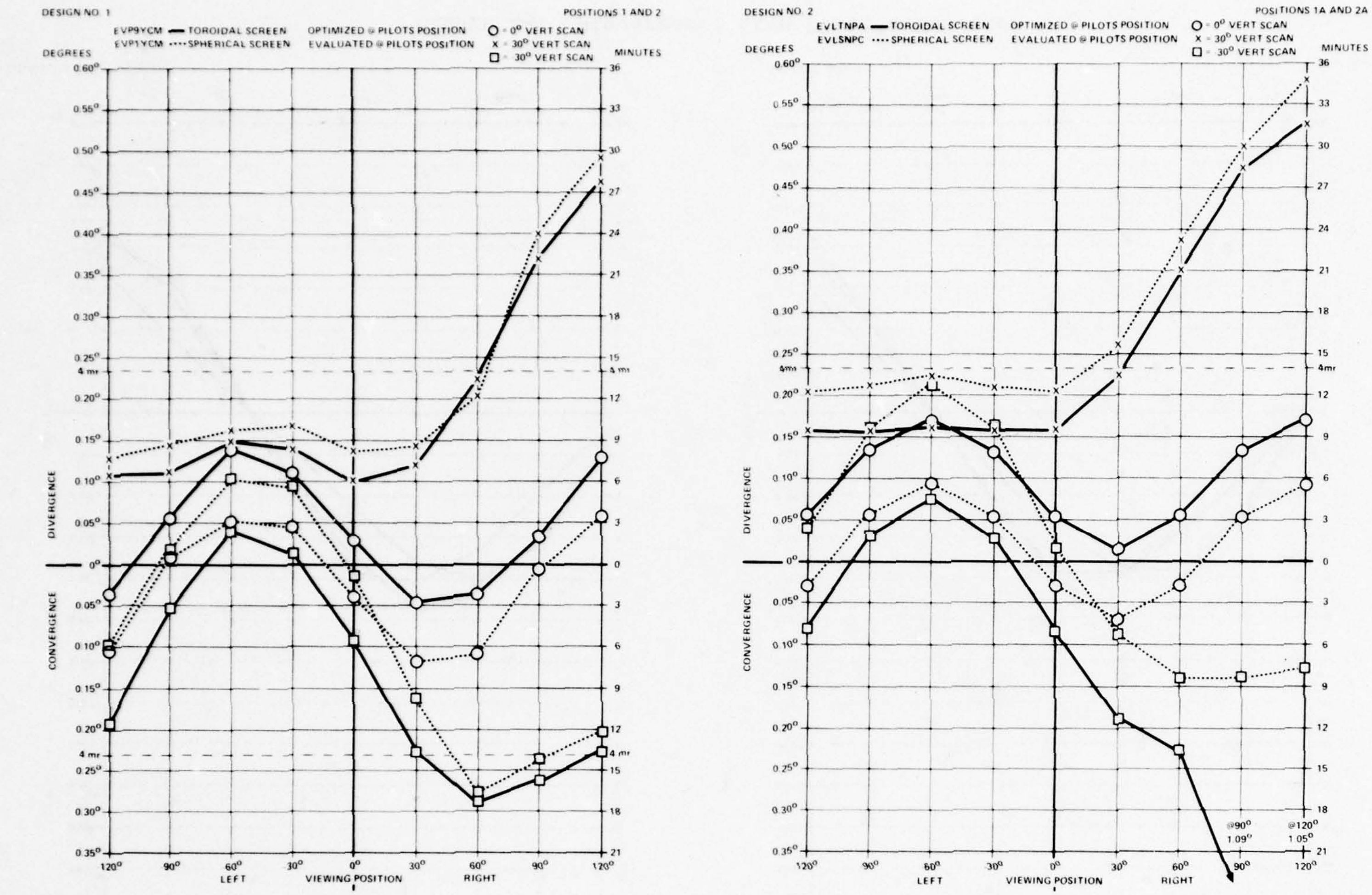


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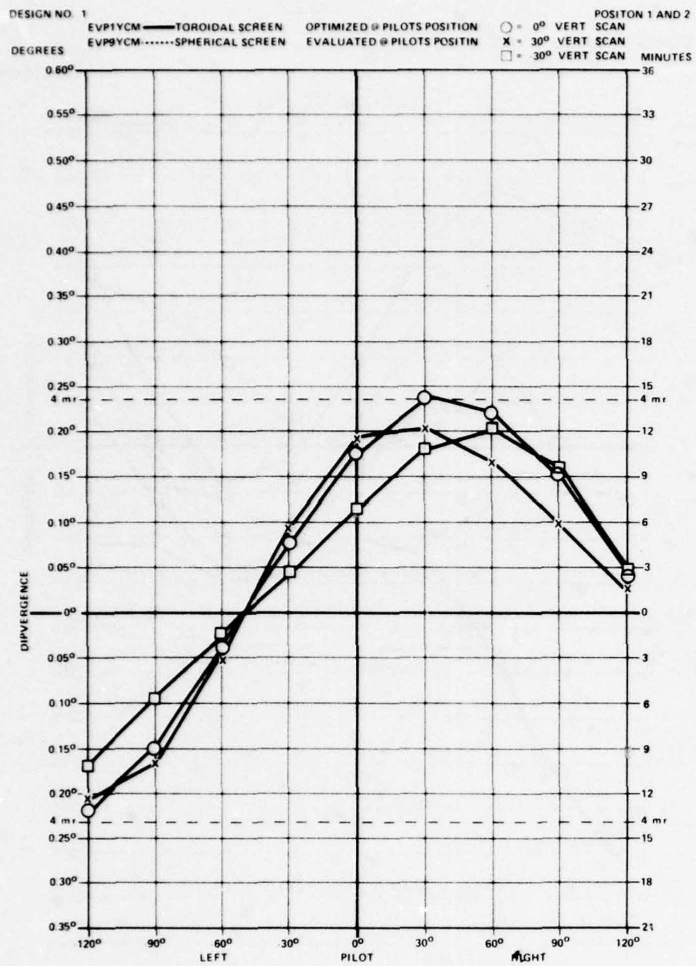
Figure 23. Collimation Data From Pilot's Position



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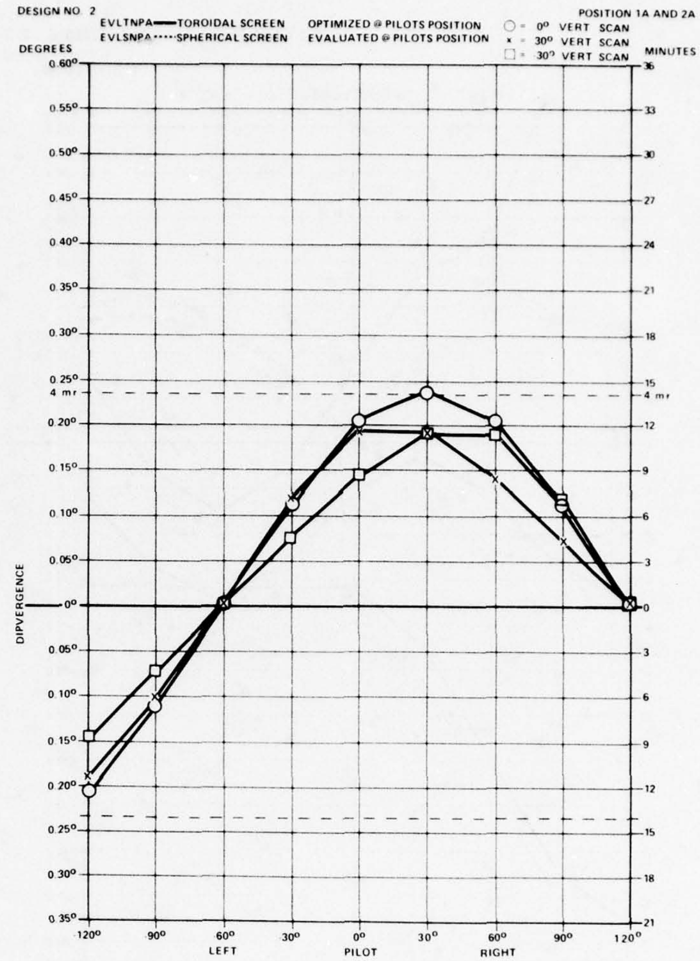

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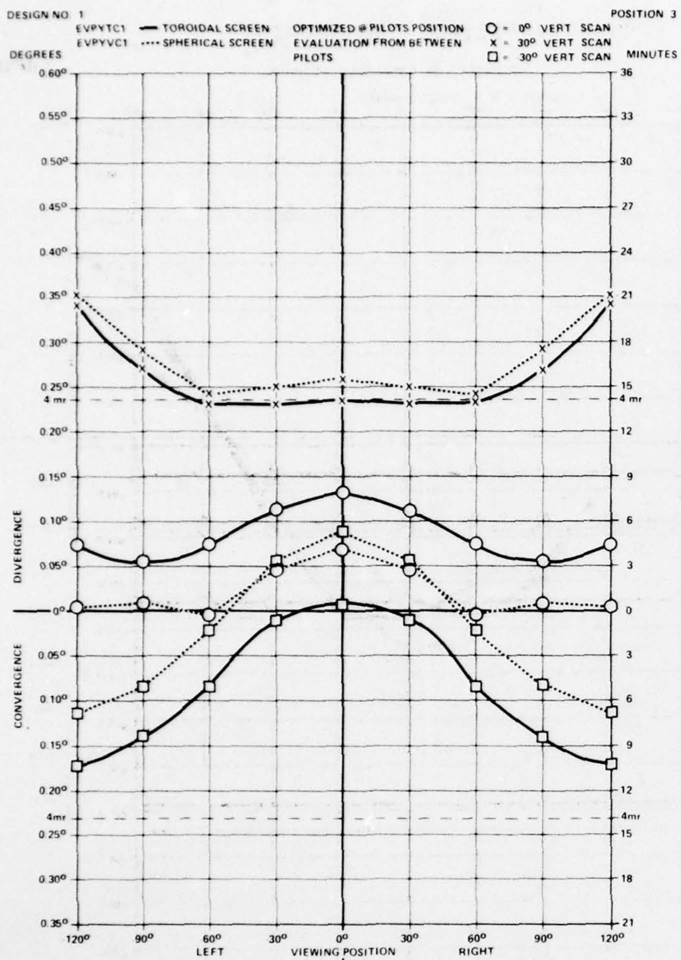
Figure 24. Dipvergence From Pilot's Position



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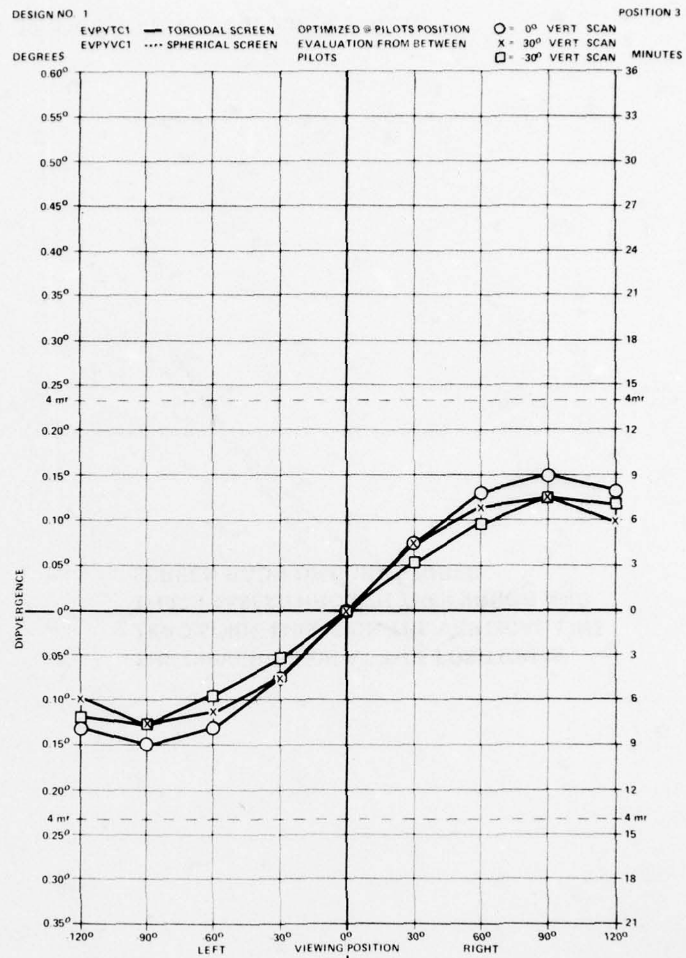

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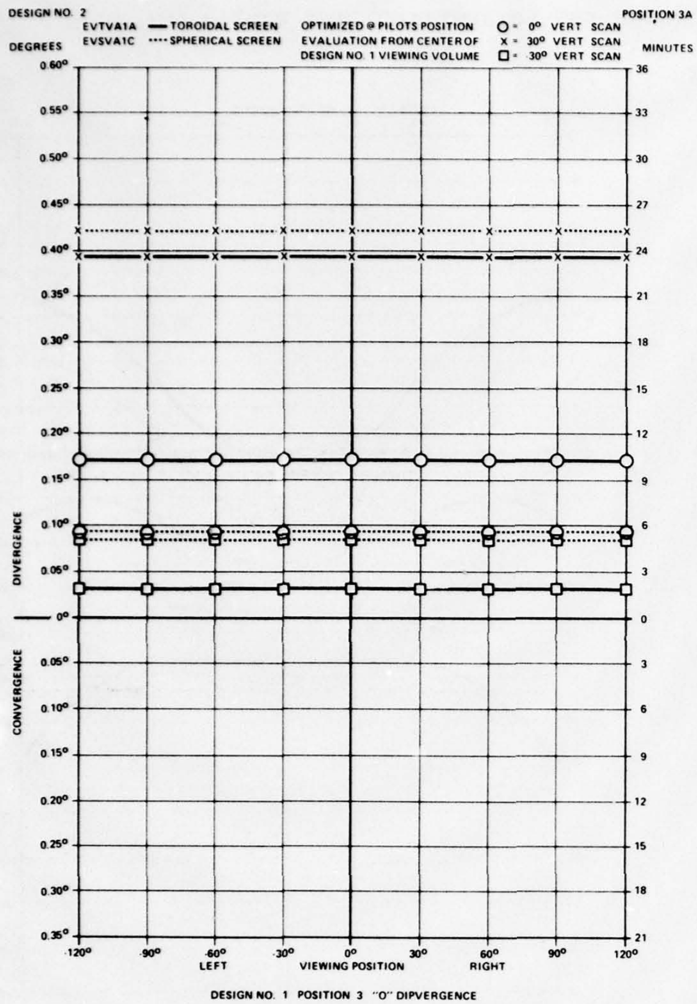
Figure 25. Collimation And Dipvergence Data From On-Line Half-Way Between Pilots



THE DIPVERGENCE AT THIS POSITION IS ZERO SINCE THIS IS ON THE VERTICAL LINE THAT PASSES THROUGH THE MIRROR AND SCREEN RADII OF CURVATURES.

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Figure 26. Collimation Data From The Center Of Curvature Axis

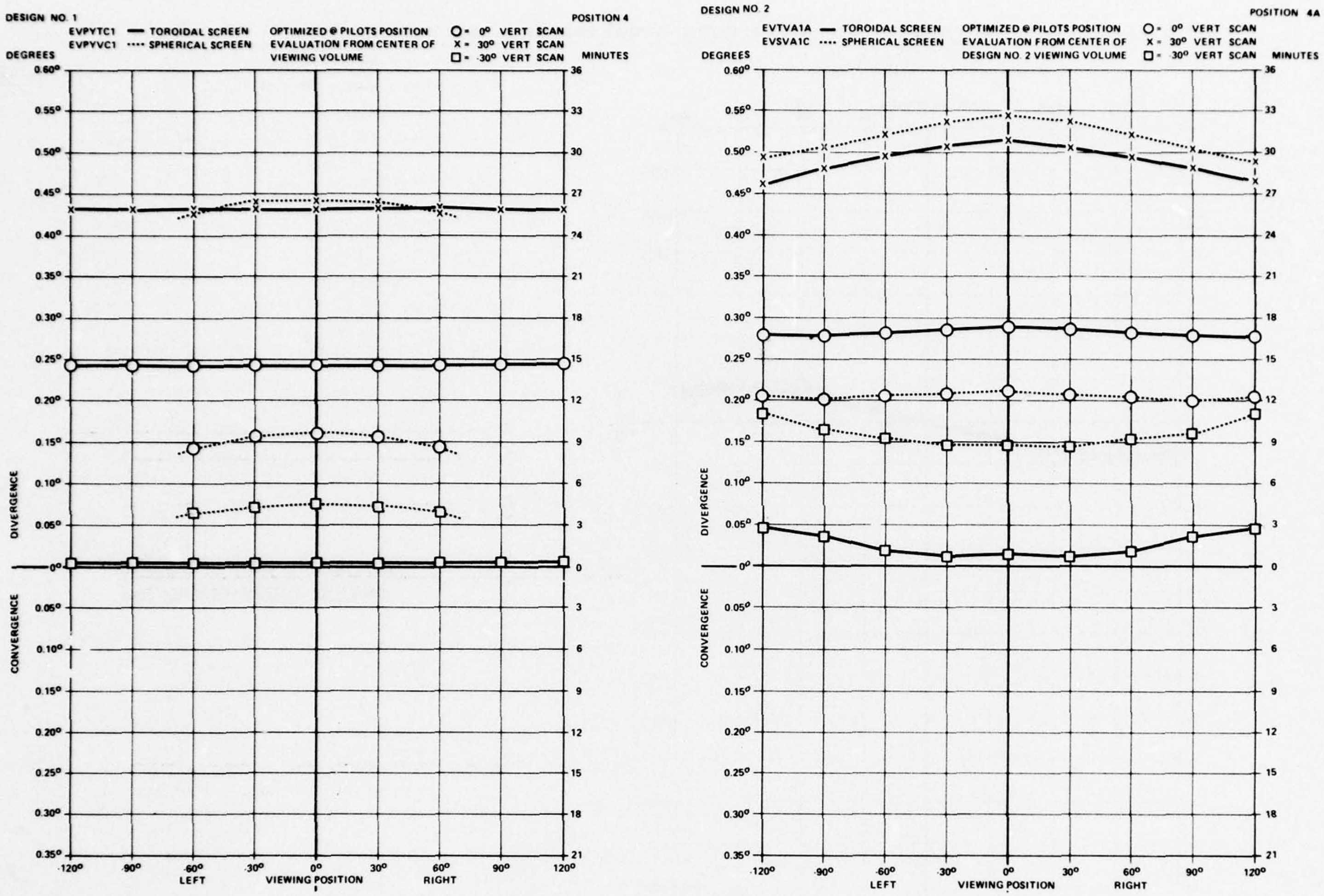

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Figure 27. Collimation Data From Central Viewing Volume

THE DIPVERGENCE IS ZERO
FOR DESIGN NO. 1; POSITION 4

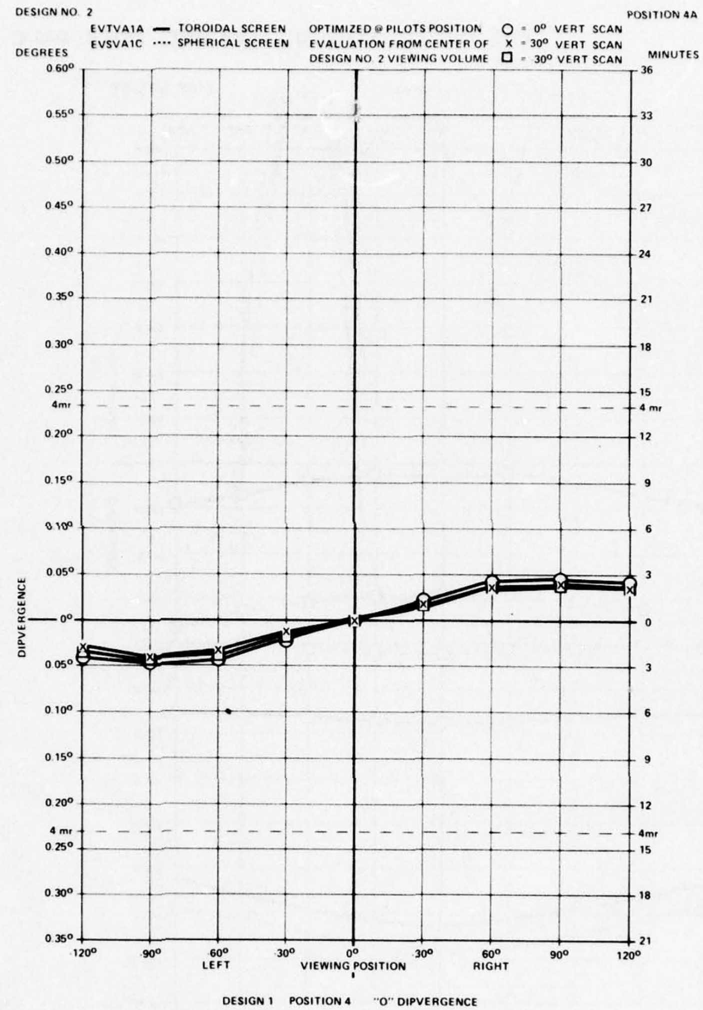

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Figure 28. Dipvergence Data From Center Design

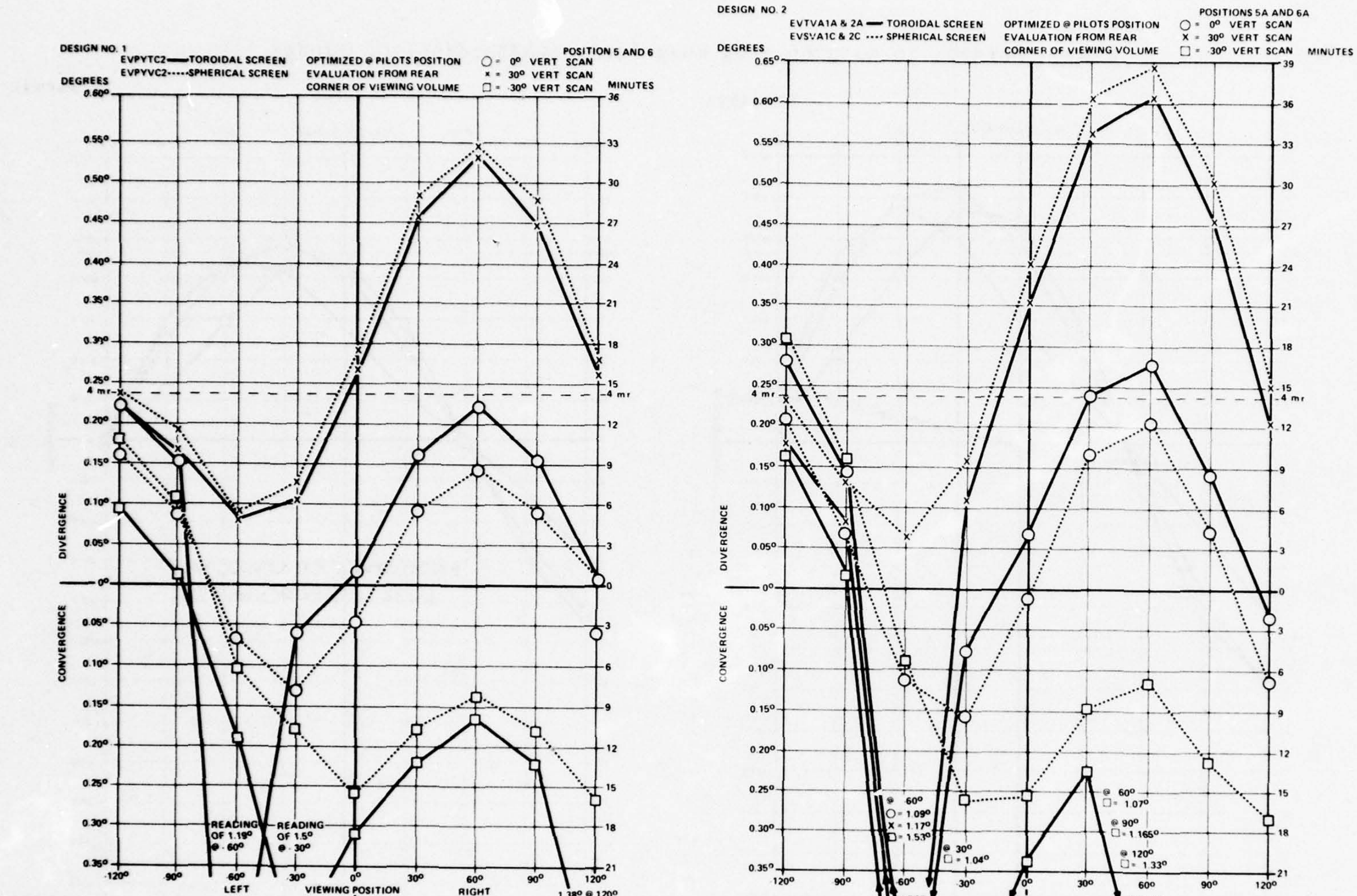

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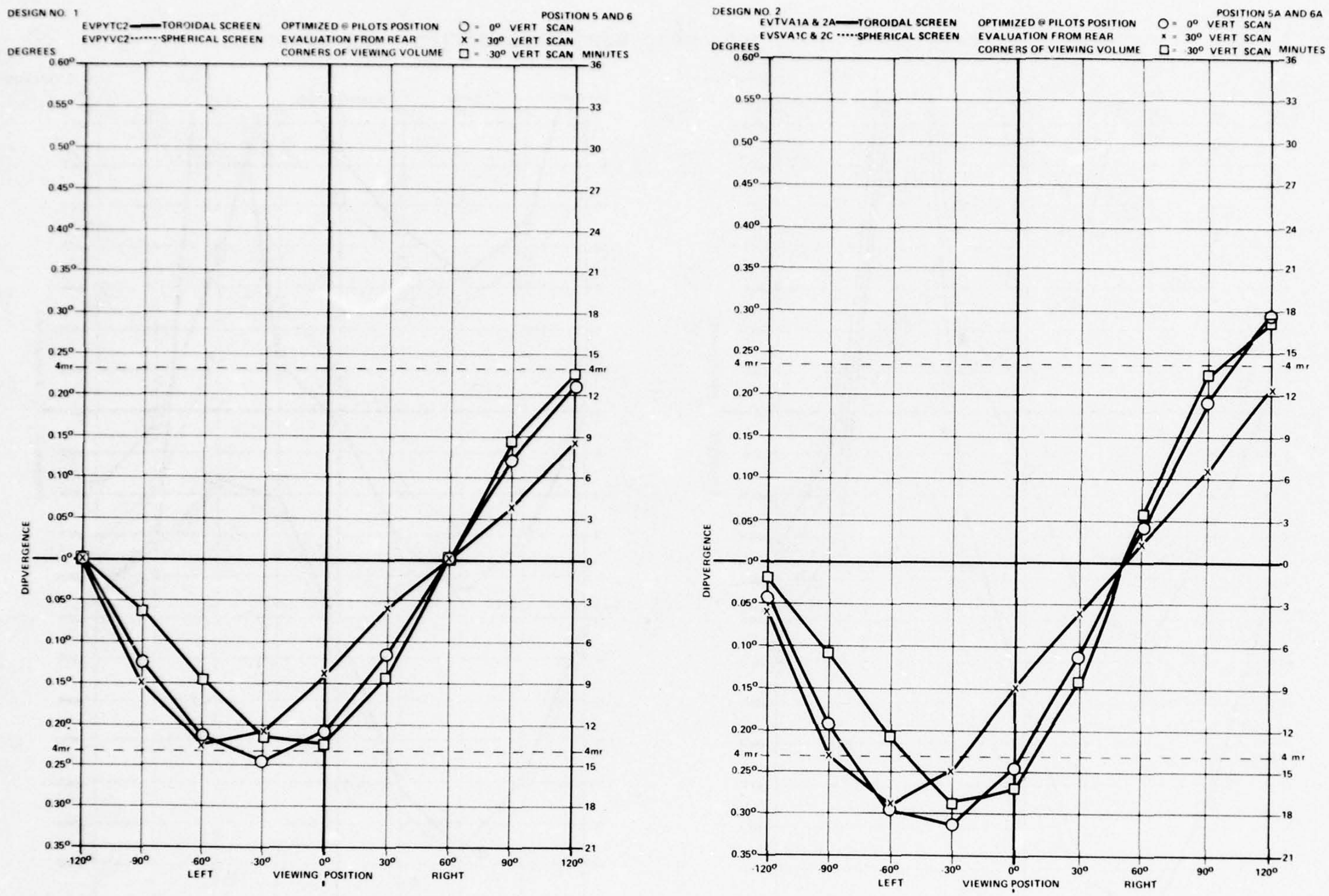
Figure 29. Collimation Data From Rear Corners Of Viewing Volume



14-655-27.2

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Figure 30. Dipvergence Data From Rear Corners Of Viewing Volume

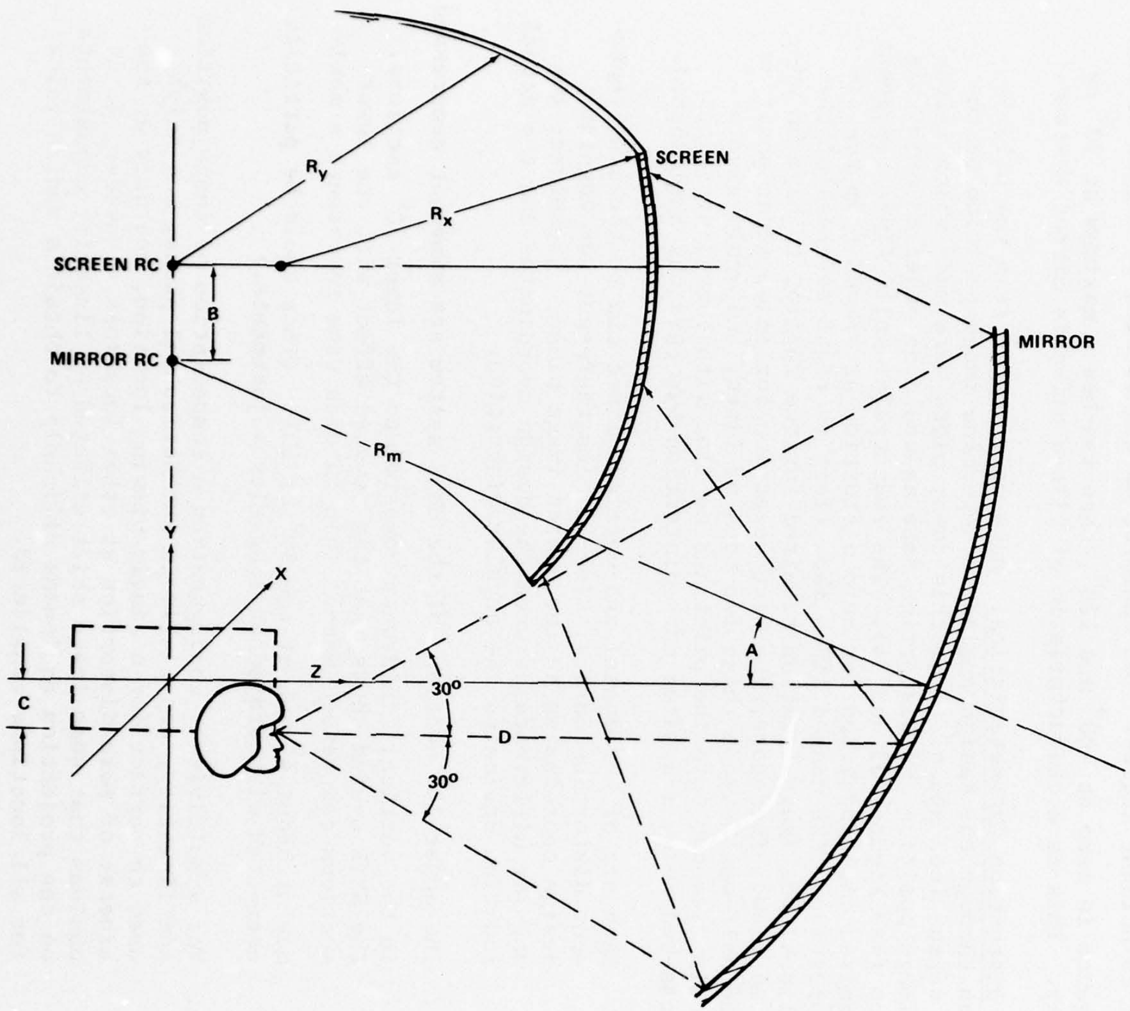

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Figure 31. Design Parameter Sketch

One interesting characteristic of the dipvergence error is that it is zero if viewed from the vertical axis that passes through the radii of curvature of the mirror and screen. See Figures 26 and 28. However, for viewing positions other than from on this line, the dipvergence will be zero only when viewed in a direction in which the ray passes through that point and intersects this vertical line (see Figure 32). Therefore the dipvergence increases as the deviation angle increases from these zero or coincident angles. For example, as can be seen in Figure 24 the dipvergence is zero at -60° and 120°, then reaches a maximum at 30° or half-way. This is a characteristic of tilted off-axis mirror systems.

6.2.1 <u>Distortion Characteristics</u>. Rays were traced from the pilot's position through the design angles to determine image position on the screen versus look angle. From this data, plots were made which illustrate image position and distortion data as would be observed from this position (see Figures 33 and 34). The rectangular solid lines represent the required image position for zero distortion as viewed from the pilot's position. The dashed lines show (left to right reversal of the solid lines) the image location required for the copilot to have an undistorted view. Therefore, the best selection for image input position would be half-way between these two sets of lines, and would give a comparable view for both the pilot and copilot with some distortion. The cross-body view indicates more distortion but this was anticipated.

a. Each set of horizontal and vertical lines can be taken to represent distortion curves. The circles represent the angular design coordinates in the design image plane. Therefore, the angular difference between the design coordinates and the actual location indicates the angular distortion.

b. The upper 30° sections of the SMSS system are somewhat compressed in the vertical field when compared to the lower 30° sections. The SMTS system shows just the reverse effect with the lower sections compressed more. This in each case represents a maximum of about 4° out of the 30° or 13%. (This could be partially corrected with projector linearity adjustments.)

c. For a multiviewer configuration a compensation of image position and linearity, especially in the horizontal plane, can only be used to correct for a single viewing location, and only at the expense of more distortion at other locations. However, it is obvious that some image shift effected by linearity adjustments on the projection equipment will help to obtain a median value for all locations considered.

d. There were two points in the SMTS system where the data values were questionable and were not plotted, but from the general trend of the curve it appears that cross-body distortion in general for this system would be worse than for the SMSS system. Note that the $\pm 120^{\circ}$ points exceed the 180° required field of view.

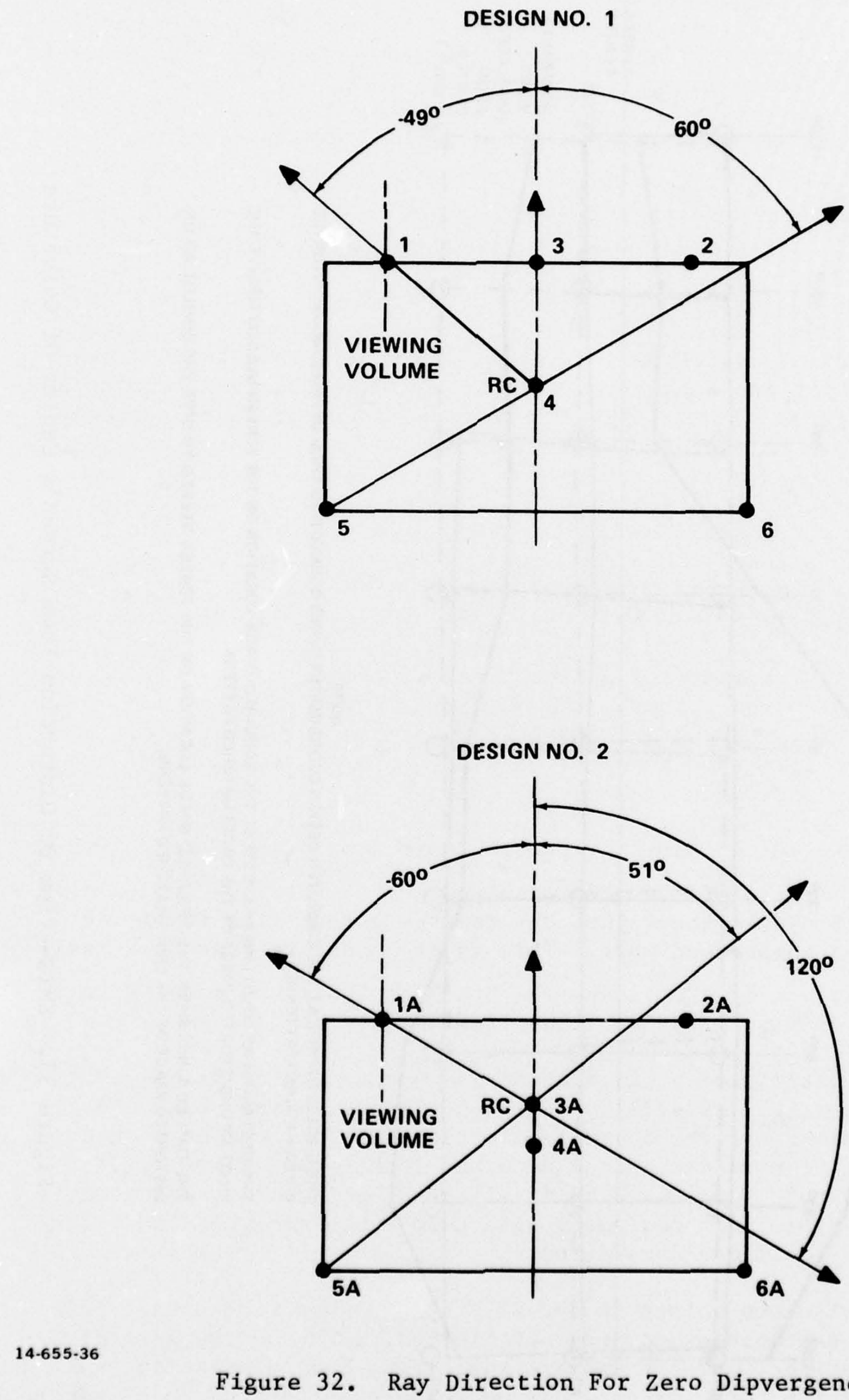
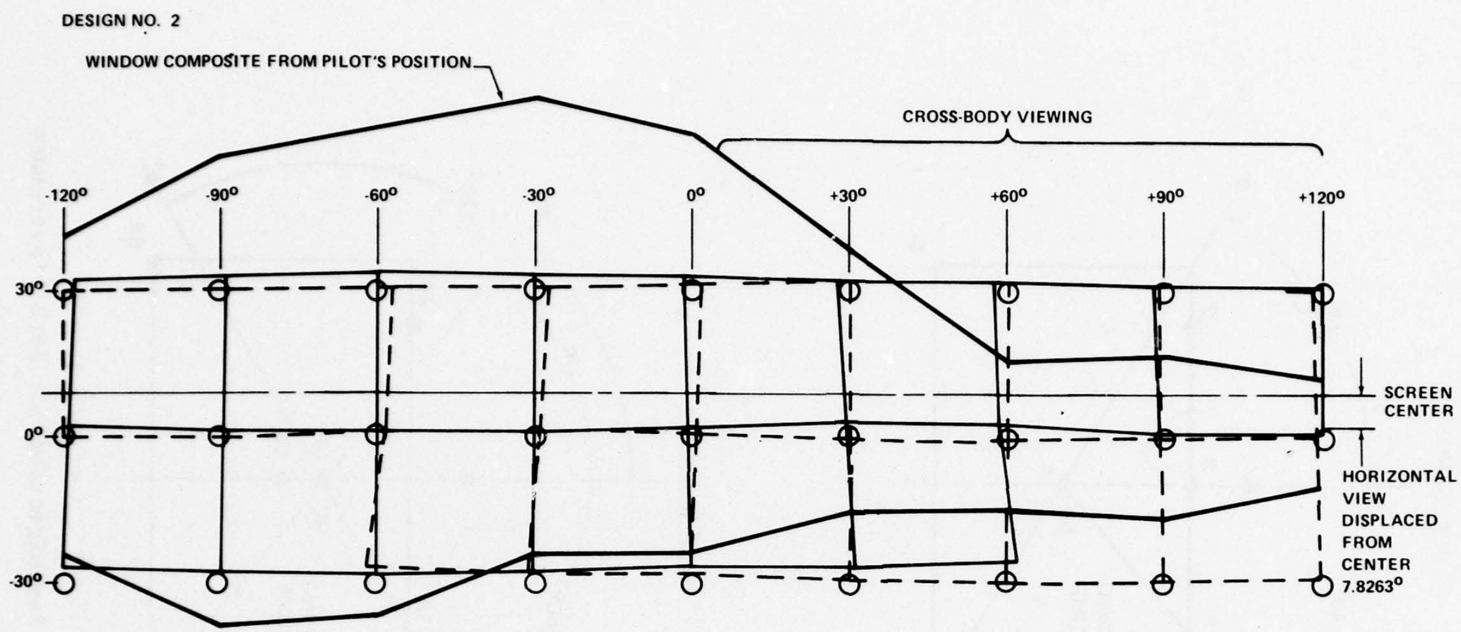


Figure 32. Ray Direction For Zero Dipvergence



NOTE

THE CIRCLES REPRESENT THE COMPUTER DESIGN COORDINATES (LINES CONNECTING THEM DEFINES AN UNDISTORTED CROSS-HATCHED PATTERN).

THE RECTANGULAR SOLID LINES REPRESENT THE REQUIRED IMAGE LOCATION ON THE SCREEN NEEDED TO GIVE THE PILOT AN UNDISTORTED IMAGE OF THE CROSS-HATCHED PATTERN.

THE DASHED LINES SHOW THE REQUIRED IMAGE LOCATION ON THE SCREEN NEEDED TO GIVE THE COPILOT AN UNDISTORTED IMAGE OF THE CROSS-HATCHED PATTERN.

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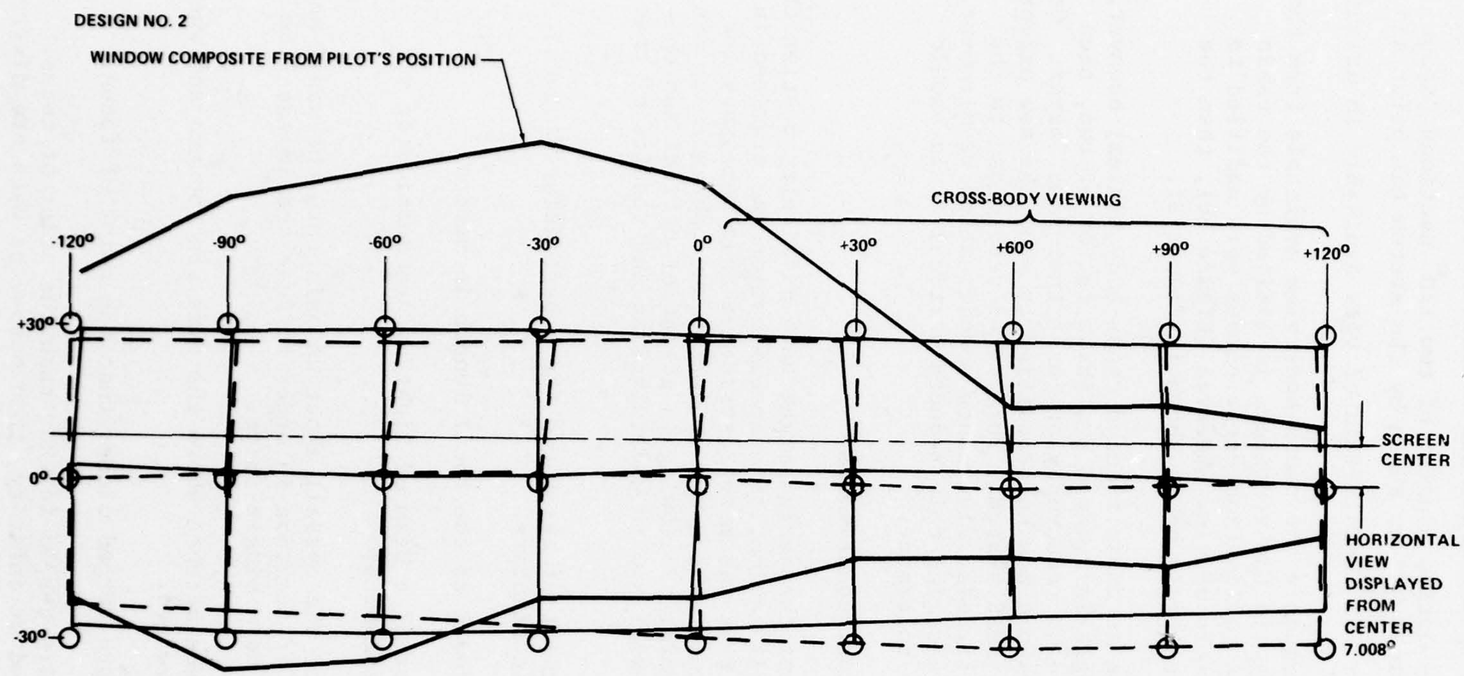
Figure 33. SMTS--View Of Distortion From Screen's Center Of Curvature



NOTE

THE CIRCLES REPRESENT THE COMPUTER DESIGN COORDINATES (LINES CONNECTING THEM DEFINES AN UNDISTORTED CROSS-HATCHED PATTERN).

THE RECTANGULAR SOLID LINES REPRESENT THE REQUIRED IMAGE LOCATION ON THE SCREEN NEEDED TO GIVE THE PILOT AN UNDISTORTED IMAGE OF THE CROSS-HATCHED PATTERN.

THE DASHED LINES SHOW THE REQUIRED IMAGE LOCATION ON THE SCREEN NEEDED TO GIVE THE COPILOT AN UNDISTORTED IMAGE OF THE CROSS-HATCHED PATTERN.

14-655-22

Figure 34. SMSS--View Of Distortion From Screen's Center Of Curvature

6.2.2 Collimation Data for Reduced Cross-Body FOV. Figure 35 shows the angles used on all the optimization and evaluation runs for the systems designed. The display optics consist of two 120° sections (about the radius of curvature axis), but as shown by the sketch the pilot and copilot actually have about 255° total field of view available in azimuth.

As mentioned and shown previously the cross-body view available from the pilot's position especially, in the vertical, is limited by the cabin windows. Therefore, if the collimation error curves were modified to correspond to the actual field of view observed (Figure 36), then the cross-body evaluation angles could be as shown in Figure 37.

Computer runs were not made at these reduced cross-body angles; however, it is known that if the angle is reduced by, say a factor of two, then the collimation error would be reduced by at least that same factor. One of the figures previously shown has been modified to show the new expected collimation errors for the SMSS system. This comes very close to the zero convergence and 4 milliradian divergence specification requirement. Further optimization runs assuming this reduced vertical field should put the errors well within tolerance.

6.3 Analysis of Collimation Requirements

When it began to appear that the design might have difficulty meeting the tentative collimation specification, this specification was examined in detail to determine whether it was more restrictive than necessary for viewer comfort. A literature search was conducted and ophthalmologists were consulted in this regard. Following is a list of optical and ophthalmic definitions which will aid in understanding the results of this study.

Accomodation - The adjustment of eye focus for a particular distance. Measured in Diopters.

Diopter - The reciprocal of the focal length in meters.

Prism Diopter - A deviation of a beam of light by one centimeter per meter. (symbol Δ)

Cyclofusion - Rotation of the eyeball about an axis thru the pupil and the point of fixation in order to fuse the images from both eyes to a single image.

Phoria - a difference between where the eyes are focused and where they are verged.

Esophoria - the eyes are verged closer than the point of focus.

Exophoria - the eyes are verged farther than the point of focus. (If focused at infinity, this means the eyes are diverging.)

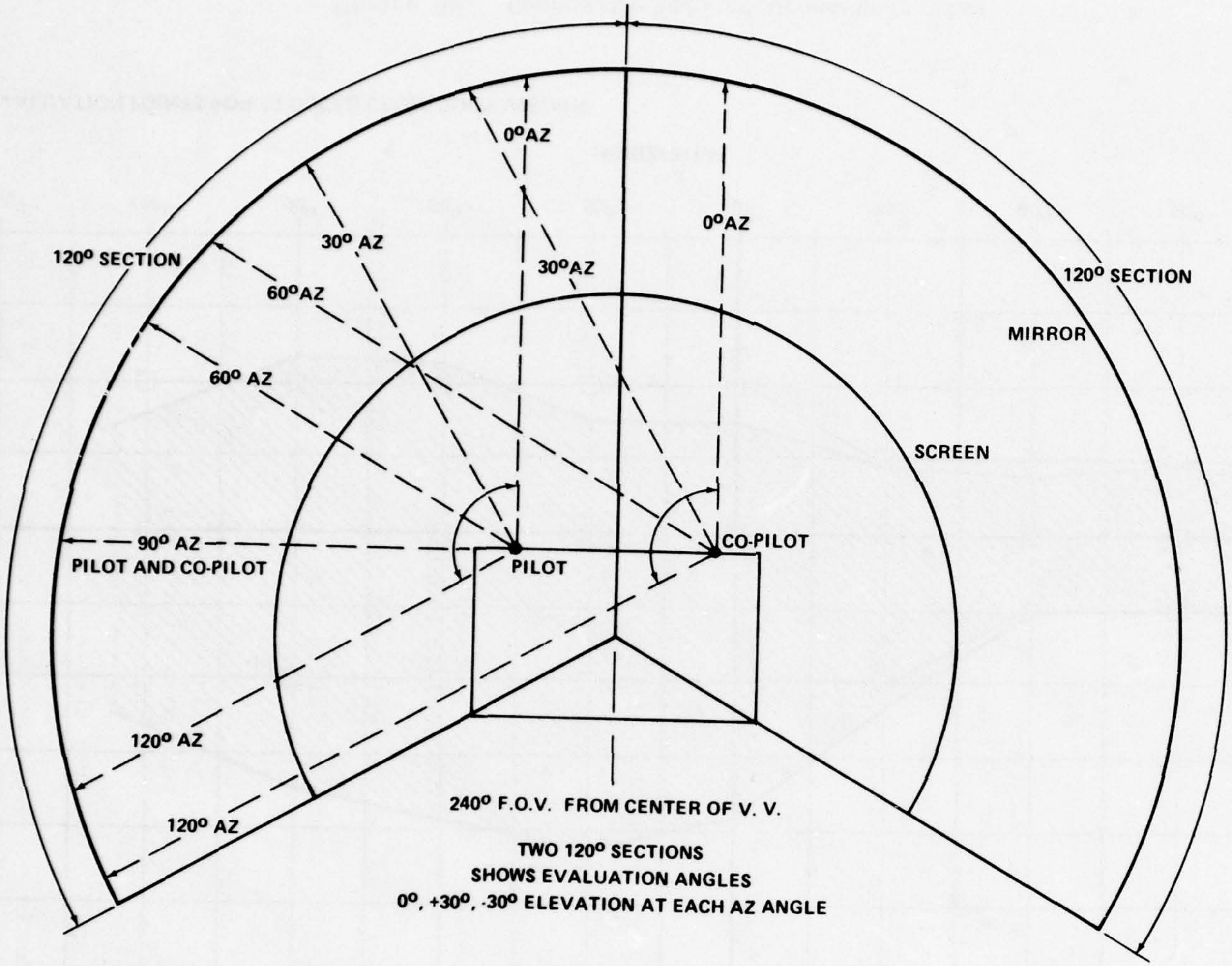


Figure 35. Design Angles

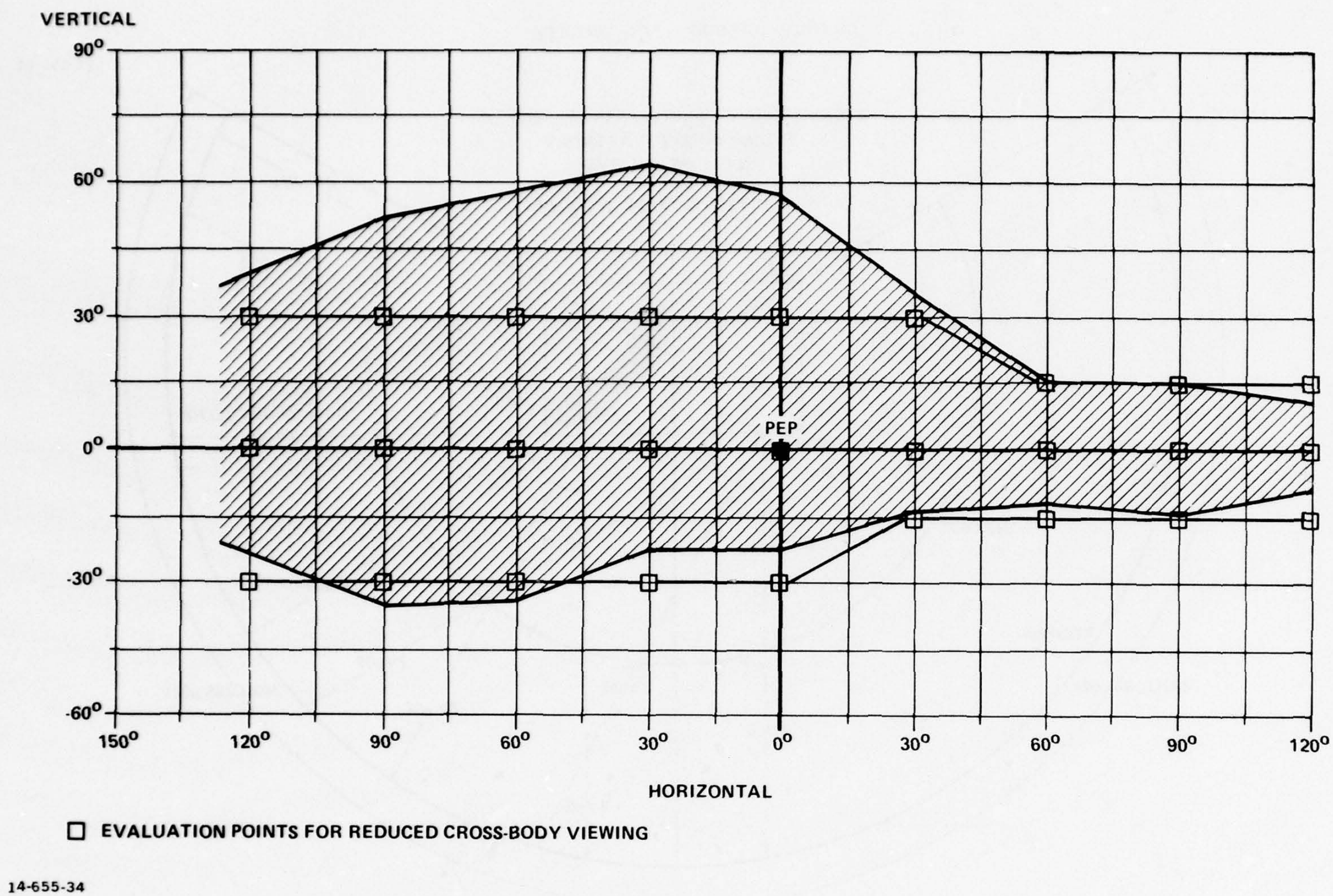


Figure 36. Composite-Reduced Cross-Body View

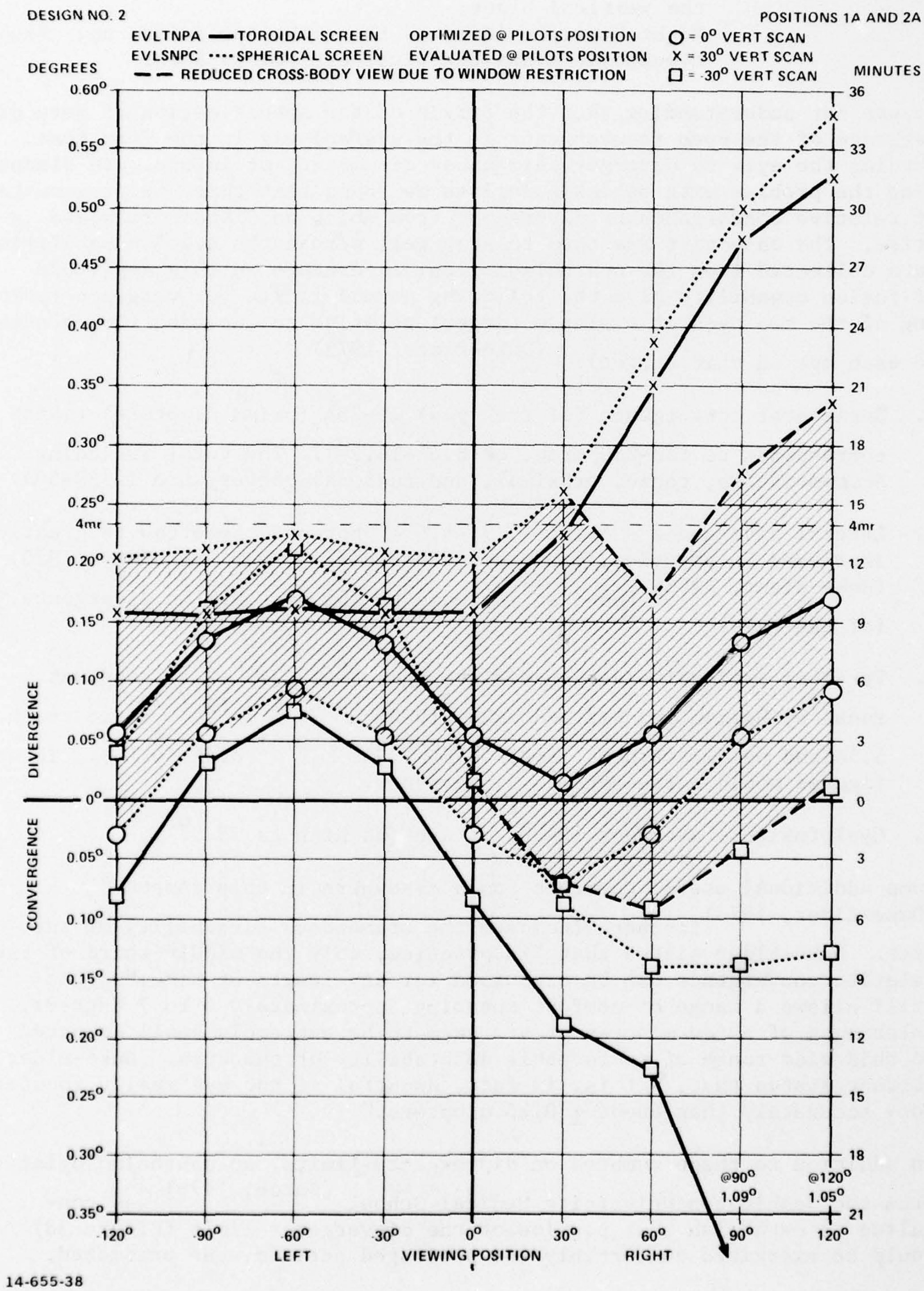


Figure 37. Expected Performance With Reduced Cross-Body View

Dipvergence or hyperphoria - the eyes point in different directions in the vertical plane.
Right hyperphoria means the right eye points up. Right hypophoria means the right eye points down.

It was our understanding that the origin of the specification of zero divergence of the eyes (convergence in the system) was in the fear that forcing the eyes to diverge would cause discomfort or injury. In discussing the problem with ophthalmologists we found that there exist amounts of relative convergence or divergence from which no discomfort would arise. The objective was then to stay well within the eyes' capabilities. Data collected from the ophthalmological literature on this amplitude of fusion capability give the following normal limits for vergence (pointing of the two eyes at a single target) relative to accommodation (focus of each eye on that target): (Duke-Elder, 1973)

1. Horizontal convergence (of the eyes) 15-25Δ (prism diopters) (which corresponds to 150-250 mrad. or 8.4°-14.2°). The total including accommodative, tonic, proximal, and fusional convergence is 30-50Δ.

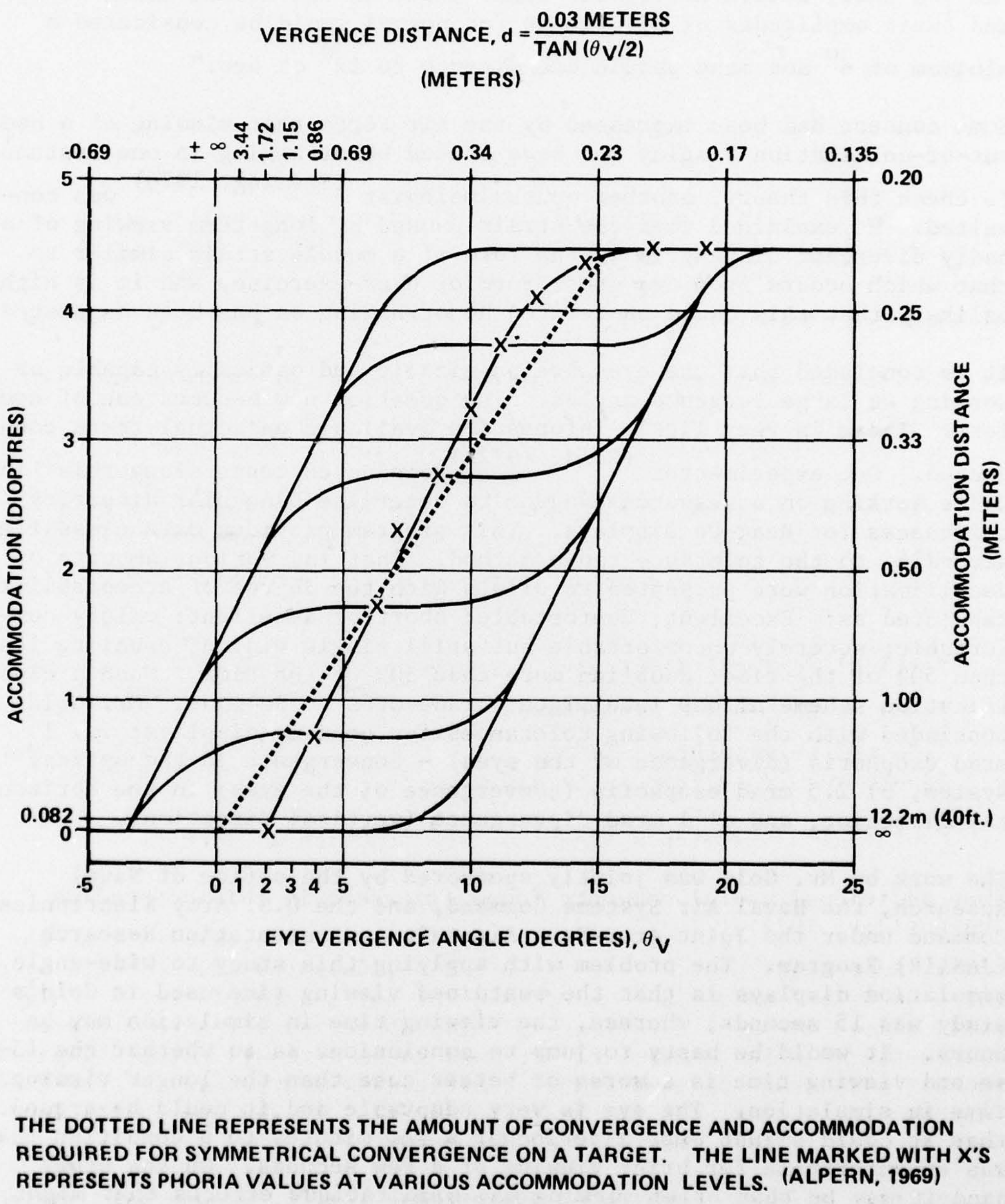
2. Lateral divergence - 8-12Δ (4.3°-6.5°) "both of these can be greatly increased on practice, convergence especially, but Jampolsky (1970) (Duke-Elder, 1973) found an increase to 40Δ possible in divergence." (of the eyes)

3. Vertical fusional divergence - averages 4-5Δ (2.2°-2.5°) and was found by Hofman and Beilschowsky (1900) (Duke-Elder, 1973) to reach 5.5Δ and by Ellerbrock (1952) (Duke-Elder, 1973) 8.4Δ (4.5°). These figures would correspond to dipvergence.

4. Cyclofusion - averages 12-20° of arc (as high as 33.9°).

Some additional useful comments found elsewhere in this compendium (Duke-Elder, 1973) further elucidate the tremendous flexibility of the eyes. Duke-Elder states that "In practice, only the middle third of the relative convergence can be exercised for any length of time." This still allows a range of comfort spanning approximately 4 to 7 degrees. Tolerances of a few minutes of arc seem to be extremely small compared to this wide range of comfortable adaptability of the eyes. Duke-Elder further states that, "It is, in fact, doubtful if the eye really focuses more accurately than about $\pm$ 0.25 diopters."

In addition to these numbers on dipvergence limits, an ophthalmologist from the Washington University Medical School (Burde, 1976) was consulted to establish what portion of the dipvergence limit (Figure 38) could be exercised comfortably for prolonged periods. He predicted,



THE DOTTED LINE REPRESENTS THE AMOUNT OF CONVERGENCE AND ACCOMMODATION REQUIRED FOR SYMMETRICAL CONVERGENCE ON A TARGET. THE LINE MARKED WITH X'S REPRESENTS PHORIA VALUES AT VARIOUS ACCOMMODATION LEVELS. (ALPERN, 1969)

Reprinted by permission from Academic Press, 1969;
Alpern, Matthew - The Eye - H. Davison, Ed, Vol. 3, New York

14-655-37

Figure 38. Typical Zone Clear Single Binocular Vision

based upon considerable clinical experience, that divergence (of the eyes) under one arc degree (17 milliradians) "would cause no ocular discomfort or fatigue over prolonged period of time." He went on to say, "As you know, active divergence takes place in all normal human beings and their amplitudes of divergence for normal would be considered a minimum of 6° and many people can diverge to 12° of arc."

Some concern had been expressed by the Air Force that viewing of a badly out-of-collimation display may have caused hemorrhaging in one instance. To check this theory, another ophthalmologist (Fleming, 1976) was consulted. He explained that the strain caused by long-term viewing of a badly divergent display is in the form of a muscle strain similar to that which occurs from any other form of over-exercise, and it is highly unlikely that this could be related hemorrhaging as has been suggested.

It is concluded that the eyes are physically and optically capable of working at large vergence angles. The question now becomes one of comfort. There is very little information available on actual tests conducted. One experimenter (Gold, 1972a) conducted tests along this line while working on a research program to determine binocular disparity tolerances for Head-Up Displays. This program provides data classified according to the tolerance range method. That is, various amounts of decollimation were presented to pilots with the degree of acceptability tabulated as: Excellent; comfortable; short of excellent; mildly comfortable; severely uncomfortable but still single vision; doubling less than 50% of the time; doubling more than 50% of the time. Such a classification scheme allows intelligent trade-offs to be made. Mr. Gold concluded with the following tolerances for head-up displays: a) 1 mrad exophoria (divergence of the eyes) - convergence in the optical system, b) 2.5 mrad esophoria (convergence of the eyes) in the horizontal direction, and c) 1 mrad dipvergence (vertical direction).

The work by Mr. Gold was jointly sponsored by the office of Naval Research, the Naval Air Systems Command, and the U.S. Army Electronics Command under the Joint Army-Navy Aircraft instrumentation Research (JANAIR) Program. The problem with applying this study to wide-angle simulation displays is that the sustained viewing time used in Gold's study was 15 seconds; whereas, the viewing time in simulation may be hours. It would be hasty to jump to conclusions as to whether the 15-second viewing time is a worse or better case than the longer viewing time in simulation. The eye is very adaptable and it could be argued that it could adjust over a period of a few minutes to a condition that was uncomfortable for brief viewing of a few seconds. On the other hand it may be that brief viewing may hide fatigue effects that might be exhibited in prolonged viewing. A test program to gather experimental data for the purpose of establishing tolerable limits of collimation errors is recommended, since over-specification is not only costly, but may eliminate systems that would otherwise be acceptable.

6.4 Possible System Characteristics Improvement and Comments

a. The most obvious and straightforward approach for reducing collimation errors would be to increase the radius of the mirror. This in effect is the same as reducing the viewing volume, decreasing the pilot separation and the eye separation of each individual observer. For example if the radius of curvature is doubled, there would be at least a 50% decrease in collimation and dipvergence errors, due to the above combined effects.

b. Since the cross-body vertical field of view is limited by the window configuration, this could be taken into consideration for the design and optimization (discussed in Section 6.2.2). In the existing designs we did not optimize for cross-body viewing, it would reduce the cross-body errors, but at the expense of normal viewing errors (0^{o} to -120^{o}) for the pilot.

c. As can be seen from the collimation data, there are both convergence and divergence errors. These curves can be shifted upward thus minimizing the convergent region by increasing the screen radius and re-optimizing selected image errors. It is not recommended that the screen be displaced forward or laterally because of symmetry of the system. The image at the extreme horizontal angles would become degraded and more convergent.

6.5 Conceptual Mechanical Design

Figure 39 is a conceptual sketch showing the component location. Either three or four 1,000-line-resolution TV projectors are used to cover the 240^{o} horizontal field of view, depending on the selected resolution. Each projector covers either a $60^{o} \times 60^{o}$ field, 3.6 ar c minutes resolution, or an $80^{o} \times 60^{o}$ field with 4.8 arc minutes resolution. The input images are edge registered without overlap and the gaps between adjacent fields would be held to less than one degree.

The mirror is made of a lightweight honeycomb material which gives ample support without excessive weight. The screen is a self-supporting acrylic material formed to the required shape with a diffusing surface either etched into, or applied to the surface nearest the mirror.

The projector distance from the screen is not fixed and is a function of the projector optics. The input image will most likely have to be coupled into the system with mirrors due to large physical dimensions of the projectors.

6.5.1 Installation Compatibility. An estimate of size and weight is given in Table 9. The weights are approximate and are based on assumptions, since no mechanical design has been made. (Note assumed mirror and screen material and thicknesses in Table 9.)

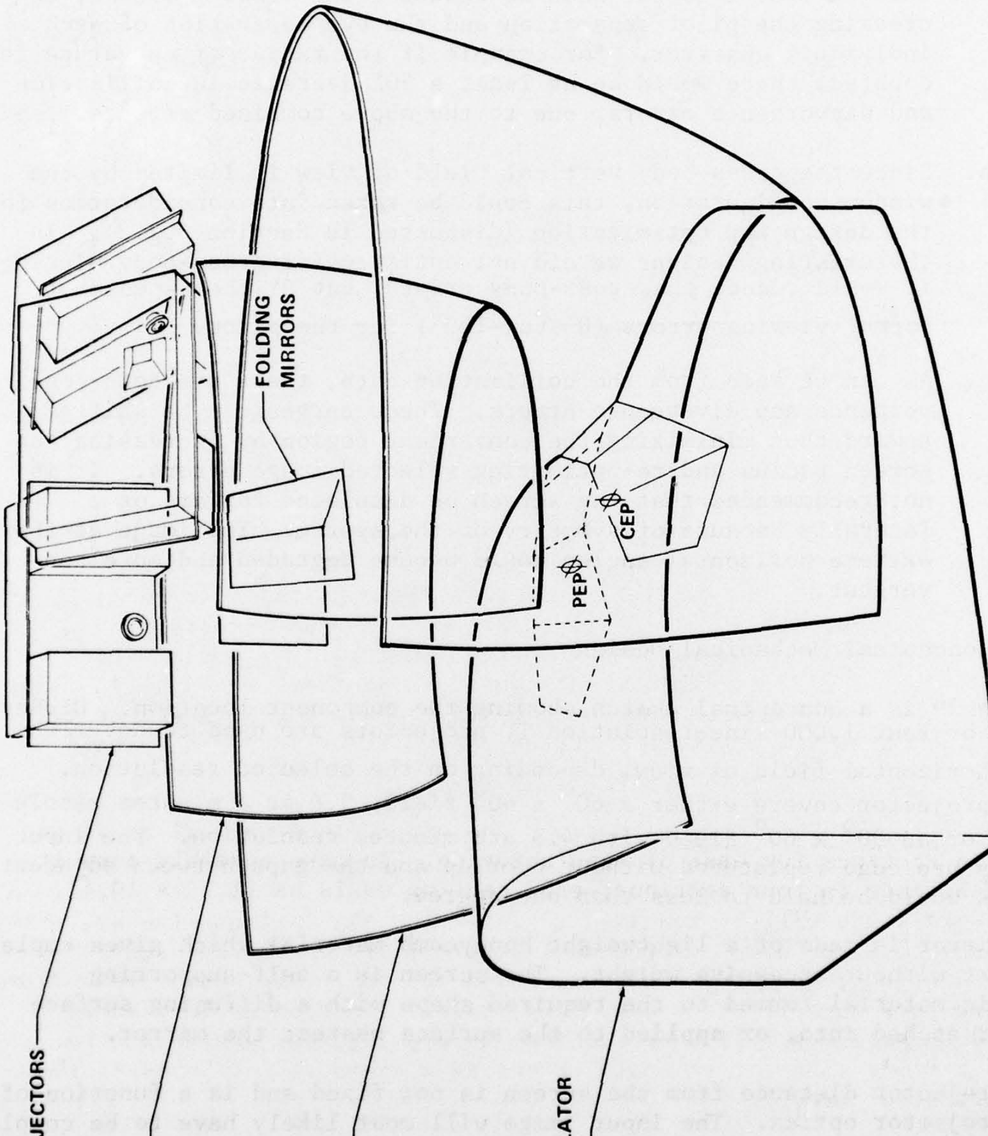


Figure 39. Conceptual View Of Off-Axis System

TABLE 9. SELECTED SYSTEM PHYSICAL CHARACTERISTICS

		Coverage (degrees)	Radius (feet)	Arc Length (feet)	Thickness (Inches)	Weight (lbs)
Mirror	Horizontal Vertical	[b] 240 60	11.0 11.0	46.1 10.4	2.25 (Honey-comb)	1,245
Screen	Horizontal Vertical	240 60	6.55 6.55	27.4 6.5	0.25 (Acrylic)	275
TV Projectors (3 ea)	Horizontal Vertical	80 60	270 lbs ea			810
Folding Mirrors	3 ea approximately 24" x 24"				0.25	40
Support Structure						1,000
	Total Weight					3,370

[b] Pilot and Copilot would each see approximately 255°, Section 6.2.2. It must be kept in mind that this system covers more than the required 180° horizontal field. If this were reduced, then there would naturally be some weight reductions, but just primarily in the mirror and screen, since three projectors would still be required.

6.5.2 Manufacturing Compatibility. The mirror is spherical so it can be made in sections for ease of manufacturing. To make assembly easy it could be made in four sections; each section would be 11.5' x 10.4'. A trade-off study will be required to determine the optimum size and number of sections to be used. For example, tolerances can be held closer on small sections; however, positioning and alignment are more involved and require more support structure. The spherical screen could also be formed in sections. If four sections were used, they would each be 6.85' x 6.5'. The screen would be put in a frame and attached to the support structure.

6.6 Conclusions and Recommendations

The results of this study have shown that the best approach for achieving the required wide field of view over the 3- x 5- x 1.5- ft viewing volume is an off-axis reflective system. It has also been shown that a spherical mirror with a spherical screen is the best shape combination.

This would not apply for a single pilot application where the viewing volume is restricted, and the pilot could be positioned on the center of curvature axis of the system. (Note data Table 6.) The improvement in performance that is achieved for center design viewing of a non-spherical system is at the expense of reduced performance when viewed from off the design center. The non-spherical systems are "highly tuned" for a small viewing volume, where the spherical system is "broadly tuned" for a larger viewing volume. The shaded area in Figure 37 shows the collimation errors that can be expected from the pilot's position for the spherical design (assuming reduced cross-body viewing).

It is recommended that this system be constructed to demonstrate its feasibility. Since this is a spherical system, it could possibly be done by using two or three small mirror sections. These sections could be moved about throughout the field of view for evaluation purposes.

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APPENDIX A - VISUAL REQUIREMENTS

A.1 Review of Visual Specifications

The minimum requirements listed in the Statement of Work are given first, followed by a brief discussion and/or comments concerning the requirement. The minimum requirements are for the displayed image as viewed from anywhere within the viewing volume. It should be noted that with the exception of the comments on stereo cues these comments were placed in the appendix because they do not result from a comparable level of effort to the main body of this report but are merely comments based upon our past experience with simulator visual systems. The stereo cue comments are based on a small literature search in addition to relevant previous Internal Research and Development and Contractor Research and Development (non-HRL sponsored) experimental work. They are, however, placed in the appendix since they do not relate directly to the main body of the study effort but point to possible areas for further effort.

a. Field of View: Continuous 180 degrees horizontal, and 60 degrees vertical.
   1. The vertical and horizontal coverage is considered to be the most important requirement, for the purposes of the study.
   2. The requirement for a full 60° vertical field may be "tradeable." System utilization and target location plots should be studied to determine if the full vertical field is a necessity.
   3. Continuity may not be a stringent requirement.

b. Viewing Volume: 5 (lateral) x 3 (longitudinal) x 1-1/2 vertical feet with the bottom plane at the minimum pilot eye height and the forward plane at the maximum forward pilot position.
   1. Must all of the specifications be met throughout all the volume? Probably not. Possibly two quality levels should be specified; high quality within the pilot's regions and another less stringent set of specifications for the less critical regions.
   2. The pilot's nominal eye position should also be specified.

c. Geometric Distortion: Less than 5% throughout the field of view and anywhere within the viewing volume.
   1. Geometric distortion is of importance since it affects image registration in a mosaicked display. Small image misalignments are very easily detected.
   2. For a non-mosaicked system this could probably be better specified by including a linearity requirement. (Mapping)

d. Collimation Error: Zero convergence to 4 milliradians divergency. This has four important aspects:
   1. The observer should be able to focus on the image comfortably.
   2. The image should appear effectively at inifinity when viewed with both eyes (biocularly).
   3. The observer should be able to comfortably verge his eyes on the image and fuse the images from the two eyes if he is to look at it for extended periods. This appears to be an area requiring further investigation, including actual tests. (Further discussion on this parameter is included in Section 6.3 of this report.)
   4. Collimation is tied to "swimming" or abnormal motion of the image as the head is moved about the pupil. Excessive change of collimation with small head motions about the nominal eyepoint could result in false parallax and distortion variations which together cause the image to "swim." It is this swimming which will practically determine the collimation requirements rather than the comfort of the eye as is further discussed in Section 6.3 of this report.

e. Resolution: 6 arc minutes, center; 8 arc minutes corner; assuming three 1,000 scan line and 1,000 TV line resolution television inputs.
   1. The 6 arc minute minimum does not agree with the 1,000 line TV over the 60° vertical field. This should be 3.6 arc minutes.
   2. This should be sufficient for most applications.

f. Highlight Brightness: 6 ft. lamberts
   1. It should be made clear as to whether this specification refers to a maximum brightness which the system would be capable of operating at without damage, or to a recommended normal operating maximum brightness. The absolute maximum brightness could be achieved for a test, to meet a specification; however, the manufacturer may not recommend that it be operated at that level in the interest of extended life.

g. Brightness Variation: Less than 25% over the entire field of view.
   1. This specification most likely can not be met, and it is unlikely that it would be noticeable (only at very low levels).
   2. A very wide-angle diffuse screen (low gain) would be required to approach this over the viewing volume, assuming a perfectly uniform input image were provided.

h. Contrast Ratio: 20:1, assuming 25:1 from the television input.
   1. This specification is not particularly tight and should be met relatively easily by the system design proposed in this report.

i. Joints: If the display is mosaicked, less than a 30 arc minute gap in the imagery.
   1. This specification could obviously be loosened in cases where the joint falls behind some piece of cockpit structure, and sufficiently close not to cause head motion to reveal it.

j. Image Registration: If the display is mosaicked, the discontinuity of the image across a joint shall be less than one degree when viewed within the viewing volume.
   1. Critical for mosaicked system - should be tighter depending on how close adjoining fields are. As little as 0.1 degree has been found objectionable on visual systems delivered by MDEC for military use.

k. Color: The optics shall be color corrected with minimal color shift and minimal color variation across the field of view.
   1. The fact that color is there is important for some functions such as aircraft carrier landing aids, Visual Approach Slope Indicator, obstruction avoidance, etc. But the fidelity of this color is relatively unimportant. However, chromatic abberration must be controlled in order that resolution requirements not be degraded. In addition, the colors of adjacent displays should match to a tighter tolerance than the variations allowed within a single display.

l. Mapping: The system shall provide a linear image to the pilot using a linearly scanned television image input device.
   1. This would be covered in the geometric distortion specification.
   2. Linearity adjustments on the television scanner would be most beneficial; otherwise, additional optics would probably be required to provide correction.

A.2 Stereo Cues

We have reason to believe that stereo depth cues are more important for certain flight tasks than is currently admitted in the simulation community. It is suspected that in certain cases where pilots have more difficulty in the simulator than in the real world, this difficulty may derive in part from lack of stereo depth cues, although it is often attributed to other causes. Examples are:

1. Difficulty in judging flare height and rate of descent when near the ground (altitudes at or below 50 feet);
2. Difficulty in formation flight;
3. Difficulty in air-to-air refueling at boom operator's station and receiver station;
4. Air-to-ground attack difficulty in judging altitude.

With respect to the air-to-air refueling task, McDonnell Douglas has built a stereo boom operator station simulator (Zamarin, 1976). Studies were conducted to determine the effects of camera baseline separation for different scene distances. The camera baseline separation was varied from zero (monoscopic) to twelve inches, and more in certain tests.

It was found that the best average, or overall, performance was achieved with an eight-inch separation for the particular system used. It was also found that stereo was superior to a monoscopic presentation even though a number of monocular cues were present. It was also found that the stereo presentations were much less affected by reductions in intensity as compared to the monoscopic system, thus showing superior operation under dimly lit conditions.

In general, stereo cues must be considered within distances of about 600 meters or less. A paper by Gold (Gold, 1972b) points out that stereo cues are dominant to a distance of 210 feet after which differential retinal size predominates if a difference in distance of multiple objects is being judged; otherwise, stereo would predominate out to its threshold limit of between 400 and 6,800 meters (depending upon stereoacuity and training of the observer). It may well be possible to provide these stereo cues in a low-cost, full-field simulation display. This is an area which might usefully be further investigated.